ISO–LWS observations of the two nearby spiral galaxies: NGC6946 and NGC1313

Alessandra Contursi[1,2], Michael J. Kaufman[3,4], George Helou[1,2], David J. Hollenbach[4], James Brauher[1], Gordon J. Stacey[5], Daniel A. Dale[1,2], Sangeeta Malhotra[6], Monica Rubio [7], Robert H. Rubin[4], Steven D. Lord[1]

Received ______________; accepted ______________

[1]IPAC, California Institute of Technology 100-22, Pasadena, CA 91125

[2]Downs Laboratory of Physics, California Institute of Technology, Pasadena, CA 91125

[3]Dept. of Physics, San Jose State University, San Jose, CA 95192-0106

[4]Space Sciences Division, MS 245-3, Nasa Ames Research Center, Moffett field, CA 94035

[5]Cornell University, Astronomy Dept. 220 Space Science Building, Ithaca, NY 14853

[6]Johns Hopkins University, Baltimore, MD 21218

[7]Departamento de Astronomía Universidad de Chile, Casilla 36–D, Snatiago, Chile

ABSTRACT

We present the analysis of ISO-Long Wavelength Spectrometer (LWS) observations of the two nearby late-type galaxies NGC1313 and NGC6946. Both galaxies have been fully mapped in the [CII] Far-Infrared (FIR) fine structure line at 158 μm and some regions have been observed also in the [OI](63 μm) and [NII](122 μm) lines. We use these observations to derive the physical properties of the atomic interstellar medium, to establish how they relate with other interstellar medium components (gas and dust), and how they vary with different galaxy components like nucleus, spiral arms and disk.

The [CII] line is the main cooling line of the atomic medium. In NGC6946 and NGC1313, its emission represents 0.8 % of the infrared emission. Moreover, the [CII] emission can be spatially associated with three components: the nucleus, the star forming regions in spiral arms and the diffuse galaxy disk. This last component contributes $\lesssim$40 % in NGC6946 and $\sim$30 % in NGC1313 to the total emission.

We apply the PDR model by Kaufman et al. (1999) to derive PDR physical parameters responsible for the neutral atomic gas emission (G_0, n and T_s). The results do not significantly differ from what Malhotra et al. (2001) found by modelling the integrated emission of a sample of 60 normal galaxies. This suggests that the emission in each region under the LWS beam in NGC6946 and NGC1313 (corresponding to a linear size of $\sim$1.5 kpc) is likely to arise from a mixture of components similar to the mixture producing the integrated emission of normal galaxies. However, some regions in NGC6946 have a G_0/n ratio $\sim$2–3 times smaller than the mean value found for the normal galaxy sample (1.3), suggesting that the beam averaged contribution of a less active component in these regions is higher than its contribution in the integrated emission of normal

galaxies or, conversely, that the bulk of the integrated emission of the normal galaxies is dominated by a few active regions probably located in their nuclei.

CO(1–0) and [CII] in NGC6946 are well correlated and the mean [CII]/CO ratio agrees with the mean integrated ratios of the normal galaxies sample. This value ($\sim$ 500) is a factor $\sim$2 less than the mean ratio found for a sample of normal galaxies observed with KAO by Stacey et al. (1991). This difference is probably due to the fact that the KAO beam ($55''$) is smaller than the LWS beam ($75''$), such that the Stacey et al. (1991) KAO observations are likely to be more biased towards the nucleus of the galaxies and therefore towards more active regions. In NGC1313 only 4 LWS regions have been observed in CO(1–0), and three of them detected. The [CII]/CO(1–0) seems to systematically increase from the north-east to the south, along the S-shaped spiral arm, indicating that the interstellar medium conditions in NGC1313 are much more inhomogeneous than the conditions in NGC6946.

HI and [CII] in NGC6946 are completely de-correlated, probably because they arise from different gas components: [CII] arises principally in dense and warm PDR and HI from diffuse ($n \lesssim 3 \times 10^3$ cm^{-3}) gas. On the other hand, in NGC1313 we successfully detect two distinct gas components: a cirrus-like component where HI and [CII] are weakly correlated as observed in our Galaxy, and a component associated with dense PDRs completely de-correlated form HI as observed in NGC6946.

Finally, we find that the HI residing in dense gas surrounding the star forming regions and presumably recently photo-dissociated, constitutes a few percent of the total HI. In turn, this dense gas component produces most of the [CII] emission emitted by the atomic neutral medium, even if its contribution is lower in NGC1313 than in NGC6946. On the other hand, the [CII] emission arising from

ionized gas is higher in NGC1313 than in NGC6946.

Key words: galaxies: individual (NGC 6946, NGC1313)— galaxies: ISM — ISM: lines and bands

1. INTRODUCTION

The evolution of a galaxy is primarily summarized in its star formation history, namely the rate at which gas is converted into stars, and where within the galaxy these stars form. These two quantities depend on the thermodynamical conditions and chemical composition of the star-forming interstellar medium (ISM). Stellar radiation and evolution will in turn modify the ISM conditions, injecting electromagnetic and mechanical energy, and newly processed material into the ISM. The interplay between ISM and star forming processes is therefore the key to understanding galaxy evolution. One way to approach this topic is to study the energy budget in nearby galaxies, *i.e.* the energy input provided by stars to the ISM and the resultant cooling of the ISM. Interstellar dust is heated by stellar radiation and cools by re–radiating at infrared wavelengths. The heating and cooling of the interstellar gas are more complicated processes because, they depend on its phase (molecular, atomic, neutral or ionized), chemical composition and temperature.

In this paper we use the main atomic gas cooling lines to investigate the energy budget between stars and gas and the physical conditions of the neutral atomic gas in two late type galaxies: NGC6946 and NGC1313. These two galaxies belong to a wider Infrared Space Observatory (ISO)–Key Project sample on 69 normal galaxies[1] observed with various ISO instruments (Dale et al. (2000), Lu et al. (2001), Malhotra et al. (2001)). In particular, 60 galaxies of the sample were observed in several far infrared (FIR) fine structure lines with the Long–Wavelength–Spectrometer (LWS) instrument on board ISO (Malhotra et al. (2001)). Since most of the galaxies in the sample are smaller than the LWS beam (FHWM=75$''$) or of comparable size, most of these ISO–LWS observations provide the integrated heating/cooling properties of the interstellar atomic gas (Malhotra et al. (2001)). However, NGC6946 and NGC1313 are sufficiently close and extended that they can be fully mapped in the strongest fine structure line: the [CII] at 158 μm. NGC6946 was also mapped in the [OI] line at 63 μm in its central $\sim 6'\times6'$ while only 3 positions were observed at this wavelength in NGC1313. The centers and some other regions in the spiral arms were also observed in the [NII] and [OIII] lines at 122 μm and 88 μm. The ISO–LWS observations of

[1] The galaxies of this sample have been selected to cover a large range in B/FIR ratios, morphologies, infrared luminosities (L_{FIR}<10^{12} $L_\odot$) and to have IRAS colors characteristic of normal galaxies.

NGC6946 and NGC1313 aimed at investigating how the main ISM physical processes change depending on which component of the galaxy (diffuse disk, spiral arms, bulge) and/or which phase of the interstellar medium is involved.

[CII] and [OI] are the main cooling lines of the neutral atomic gas. In normal galaxies, [CII] usually dominates energetically, carrying a luminosity $\sim$ 0.3–1 % of the FIR luminosity (Crawford et al. (1985), Stacey et al. (1991)). The [CII] line arises from the $^2P_{3/2} \rightarrow {}^2P_{1/2}$ magnetic dipole transition of C^+ at $\frac{\Delta E}{k}$=91 K above the ground state. As the ionization potential of the C atom is 11.3 eV, it can be easily ionized by far UV (FUV) photons which escape from HII regions (h$\nu <$ 13.6 eV). The [OI] $^3P_1 \rightarrow {}^3P_2$ fine structure line at 63 μm has an excitation energy $\frac{\Delta E}{k}$=228 K. The C^+ ions and the O^0 atoms are excited by collisions with atomic hydrogen in the neutral atomic gas, with molecules (mainly H_2) in the molecular gas and (for C^+) with electrons in HII regions. The critical density is the density at which collisional de–excitation balances radiative de–excitation (Osterbrock (1974)). The critcal density for collision of C^+ and O^0 with H atoms are: $n_{crit}^{[CII]} = 3\times10^3$ cm^{-3} (Crawford et al. (1985)) and $n_{crit}^{[OI]} = 5\times10^5$ cm^{-3} (Table 4 of Tielens and Hollenbach (1985)).

[OI] and [CII] emission from the neutral ISM arise in photodissociation regions (PDRs), *i.e.* those regions in which the chemical and heating

processes are dominated or induced by interaction with FUV photons. In PDRs the gas is heated by energetic photo–electrons ejected by dust grains after absorption of FUV (6 eV < hν < 13.6 eV) photons (Hollenbach & Tielens (1999)) or, for dense (n>10^4 cm^{-3}) gas regions, via collisional deexcitation of vibrationally excited H_2 (Sternberg & Dalgarno (1989)). Since smaller grains are more efficient at photo–electron production, the smallest grains (sometimes referred to as Very Small Grains) or even large molecules (those responsible for the Aromatic Features observed in Emission (AFEs) between 5 μm and 20 μm often attributed to Polycyclic Aromatic Hydrocarbons or PAHs) are likely to be the main sources of photo–electrons and thus of gas heating in PDRs (Bakes & Tielens (1994), Helou et al. (2001)). The brightest PDRs in the FIR fine structure lines and in the infrared continuum are the dense and warm regions of interface between star forming regions and their parental molecular clouds. However, we also expect [CII] and [OI] from atomic ISM (*e.g* atomic clouds) and [CII] from diffuse ionized medium (DIM) and HII regions. It is still not clear how much of [CII] arises from each gas phase in galaxies. For example, in the Galactic interior Heiles (1994) ranked the DIM to be the most significant contributor to the observed [CII] emission in the atomic medium followed by the atomic clouds and by the regions of interface between star forming regions and molecular clouds. Madden et al. (1993) claimed that $\sim$ 70% of

the [CII] emission in NGC6946 comes from both diffuse neutral (HI) and diffuse ionized ISM. On the other hand, Sauty, Gérin & Casoli (1998), using radiative transfer models of the same galaxy, claim that only 30% of the [CII] emission arises from these ISM phases.

Using the LWS observations of NGC6946 and NGC1313 we address three topics:

1) We investigate whether the [CII] emission from different regions inside NGC1313 and NGC6946 behaves like the integrated [CII] emission of the galaxies belonging to the ISO–KP sample of normal galaxies presented by Malhotra et al. (2000), (2001).

2) We take advantage of the relatively high spatial resolution to evaluate the relative contribution of various phases of ISM to the [CII] emission.

3) We derive the local interstellar radiation field and the gas density of the neutral PDRs analyzed inside NGC6946 and NGC1313, applying the PDR model from Kaufman et al. (1999).

The paper is organized as follows: Sec. 2 presents the main characteristics of NGC6946 and NGC1313. Sec. 3 reports on the data reduction and analysis. Results are presented in Sec. 4, where first we study the relation between gas cooling, dust emission and the interstellar radiation field (ISRF) intensity and where we compare the cooling inside the observed galaxies with the global cooling of normal galaxies. We tentatively estimate the contribution

to the gas cooling associated with nucleus, spiral arms and diffuse disk. The discussion is presented in Sec. 5 where we derive the physical parameters of the PDRs in the two galaxies by comparing the PDR models by Kaufman et al. (1999) to the observations. These parameters allow us to discuss the origin of the observed [CII], HI and CO emission in both galaxies. Conclusions are summarized in Sec. 6.

2. THE OBSERVED GALAXIES

2.1. NGC1313

NGC1313, 3.6 Mpc away, is an Sbd galaxy (Table 1) with a metallicity a factor four less than that in the Milky Way[2] ($12 + log(\frac{N(O)}{N(H)}) = 8.4$, Walsh & Roy (1997)). Authors classify NGC1313 between a late type spiral and a Magellanic Irregular. It is the highest mass barred galaxy known with no radial abundance gradient (Mollá & Roy (1999)). Its HI emission extends 24 kpc, well beyond the stellar component and it exhibits HI superbubbles typical of Magellanic–Irregular galaxies (Ryder et al. (1995)). The MIR emission (7 and 15 μm) observed with ISOCAM extends only for the central $\simeq$ 8 kpc region (Dale et al. (1999)) and its distribution and extension agree

[2]We assume $< 12 + log(\frac{N(O)}{N(H)}) > = 9.04$ for the Galaxy as in Garnett & Shields (1987)

with those in the Hα line (Ryder et al. (1995)) and at 1600 $\AA$ (Kuchinski et al. (2000), this image not shown in this paper was kindly provided by B. Madore). NGC1313 was observed in the ^{12}CO(1–0) line by Bajaja et al. (1995). They report only a 3σ upper limit in the central region of the galaxy. Recently, we re–observed this galaxy in the ^{12}CO(1–0) and ^{12}CO(2–1) lines with the new more sensitive receivers at SEST (Rubio et al. in preparation). We successfully detected molecular gas in the north-east spiral arm, in the center and $\sim$3$'$ south–west from the center. No CO was detected in the south region.

An area of $\sim$ 10$'\times$10$'$ corresponding to the HI extension of NGC1313 was fully mapped with LWS at 158 μm in the [CII] fine structure line as part of the ISO–KP on Normal galaxies allocated with NASA time (Helou et al. (1998)). Figure 1 shows the full LWS coverage at this wavelength (all circles) on a HI map of NGC1313. The diameter of the circles correspond to 75$''$, the adopted LWS beam size at 158 μm. Three different pointings (blue circles in Fig. 1) were re-observed also in the [NII(122μm)] and [OI(63 μm)] fine structure lines. One of them, close to the galaxy center (region 89 in Fig. 1), has been observed also in the [OIII(88 μm)] fine structure line.

2.2. NGC6946

NGC6946 is a nearby low inclination (i$\sim$30°) Scd galaxy at a distance of 4.5 Mpc (Table 1) with an abundance gradient d[O/H]/dR= -0.089±0.003 dex/kpc very similar to the gradient in the Milky Way equal to -0.07±-0.015 (Belley & Roy (1992) and references therein). It has a nuclear starburst and a weak central bar with an associated gas flow where star formation is taking place (see Elmegreen, Chromey & Santos (1998) and references therein). This galaxy shows a well pronounced open spiral pattern as well as extended emission visible in the HI line, radio continuum, FIR, and MIR emission. Its north–eastern arm is the brightest arm at all wavelengths indicating a site of vigorous star formation. Previous KAO observations in the [CII] line were presented by Madden et al. (1993). These data show a maximum of emission in the starburst nucleus, a component well correlated with the main spiral arms, and a smooth component which the authors associate with the diffuse medium (both neutral and fully ionized) and which accounts for $\sim$ 70% of the total [CII] emission. The ^{12}CO(1–0) and ^{12}CO(2–1) emission from NGC6946 is rather extended over the galaxy and it is mostly associated with the nuclear region and the Spiral Arms. Casoli et al. (1990) found a low ^{12}CO(2–1) over ^{12}CO(1-0) ratio, averaged in 23$''$ beam size, of about 0.4 in the NGC6946 disk, suggesting H_2 gas densities between 150–1500 cm^{-3} associated with cloud envelopes rather than cloud cores. The same ratio

is ~ 1 for the central starburst region, which points to higher density and excitation conditions in the nuclear starburst, as expected. The HI surface brightness variation is also low (a factor of $\sim$ 2-3) in a $\sim 25''$ beam, as reported in Boulanger & Viallefond (1992) corresponding to a minimum and maximum deprojected HI column density of 3.6×10^{20} and 9.5×10^{20} cm^{-2} respectively. In contrast to the molecular gas, which peaks on the central starburst, the HI distribution has a minimum in this region. Finally, ROSAT X–ray observations of NGC6946 show no evidence of hot diffuse interstellar gas (Scott et al. (1998)). The bottom panel of Fig. 1 shows the LWS coverage at different wavelengths superposed on the HI map of NGC6946.

3. LWS data reduction and analysis

The data were processed through the LWS Pipeline (OLP) Version 7.0. Most of the regions observed in NGC1313 and NGC6946 are in the faint flux regime ($F_{60\mu m}$<50Jy in the $75''$ beam). Therefore, the continuum fluxes in the LWS spectra are affected by the errors in the dark current which can be of the same order as the continuum flux. To correct for this, the dark currents were re-estimated and removed using the LWS Interactive Analysis (LIA). However, since the dark currents are only additive in nature, they do not affect our line flux estimates. With LIA the data were then corrected for any instrumental responsivity variations and the flux calibrated to the LWS

calibration source Uranus. Glitches due to cosmic rays were removed from the data using the ISO Spectral Analysis Package (ISAP). For a complete description of the LWS observation modes see Brauher (in preparation). Spectral scans were co-added and averaged together using a 3-σ clip in spectral bins of about 0.05 μm. For the L01 observation of the center of NGC6946, a sinusoidal fringe associated with the LWS instrument was removed using a defringing algorithm supplied within ISAP. All spectral lines in our study are unresolved. After fitting a linear baseline to the data, the line fluxes were calculated assuming a Gaussian line with an effective instrumental profile of 0.29μm for $\lambda <$ 90μm and 0.60μm for $\lambda >$ 90μm ($\Delta v \sim 10^3$ km s^{-1}). The uncertainties associated with each line flux were estimated as the product of this effective instrumental width and the *r.m.s* of the linear baseline fit to the data. In the case of non-detections, 3-σ upper limits are calculated.

The final flux measurements with associated uncertainties of the FIR lines observed are shown in Tables 2 and 3 for NGC1313 and Table 4 for NGC6946. The uncertainties listed are those derived from the line and baseline fitting only. They do not include the absolute uncertainties ~30%. As shown in Fig. 1, we observed the two galaxies in the [CII] line over their optical extent (R_{25}). However, since the LWS pointings do not satisfy the Nyquist sampling criterion and the LWS beam at 158 μm is significantly

smaller than the diffraction value, we will not use the interpolated maps for the quantitative analysis. We instead use the single pointing measurements. To compare the measured flux in each LWS pointing with the emission at other wavelengths (21 cm, ^{12}CO(1–0),HiRes IRAS, ISOCAM) we proceed as follows. We assume a Gaussian LWS beam whose FHWM is 75″, the mean value published in the latest LWS technical report (Gry, Swinyard, Harwood et al. (2000)). We then extract the flux at other wavelengths with two methods: 1) on the images smoothed to the LWS resolution by multiplying the peak value by the assumed beam area 2) by summing the flux from the (unsmoothed) mid and far infrared continuum, HI and CO line images using a Gaussian weighting with a σ_{gauss} determined by the 158 μm beam characteristics, centered at each 158 μm pointings. The two fluxes thus obtained are compared for each wavelength and show typical differences of about 1%. However, these two methods differ by 7% in two cases, namely the HI map, and the IRAS High resolution images. This is due to the fact that the PSFs of these images are not perfectly circular as assumed.

Another source of error arises from the uncertainty on the adopted LWS beam size. For each wavelength other than [CII], the map is convolved with the adopted LWS beam and the resulting flux compared to the observed [CII] flux at each pointing. In order to estimate the uncertainty, we explore a range of LWS beam sizes corresponding to 1σ on the adopted size, namely

70″, 75″, 80″ and 90″. For each of these sizes Ω, we recompute the fluxes and analyze the correlation with [CII], re-deriving the dispersion around the best fit of the form:

$$f(\lambda, \Omega) = \mathrm{a}(\Omega)\ \mathrm{f}([\mathrm{CII}])^{\alpha} \tag{1}$$

As Ω is varied, the dispersion changes too. Assuming that the increase in this dispersion is primarily due to using the wrong value of Ω, we can estimate that contribution for the $\pm 1\sigma$ range as the contribution to be added in quadrature for the change in dispersion to obtain.

We performed this calculation for the ISOCAM images in LW2 and LW3, and for the 4 IRAS bands, and obtained uncertainties ranging from 9% to 16%. We stress that this procedure is not intended to find the correct ISOLWS beam size, but rather to estimate the uncertainty on the calculated fluxes due to an imprecise knowledge of the ISOLWS beam size. We also point out that this is an overestimate of that uncertainty, since other effects might contribute to the change in the dispersion, such as an intrinsically non-unit value of α, or the intrinsic gradients in the brightness of the galaxies at various wavelengths.

In conclusion, the total percent uncertainty in the flux at other wavelengths is $\sqrt{7^2 + unc^2(\Omega, \lambda) + rms^2(\lambda)}$, where the $rms(\lambda)$ is the original noise in

each image at each λ divided by the flux in each LWS pointing.

A reference position has been observed several times for each galaxy providing the background value. However, inspection of $2.5^{\circ}\times2.5^{\circ}$IRAS images at 100 and 60 μm for both galaxies revealed extended Galactic infrared emission in the direction of NGC1313 only. No such structure in the Galactic emission is evident in the direction of NGC6946. Fig. 2 shows the HI contours superposed on the IRAS 100 μm image for NGC1313. Also marked in the north–west part of the frame is the position of the reference point observed with LWS. It is clear that this reference point underestimates the average Galactic foreground emission in the NGC1313 direction. The Galactic contribution estimation at 158 μm in the direction of NGC1313 is described in Appendix 1 and it is equal to $11\pm5\times10^{-14}$ erg s^{-1} cm^{-2} beam^{-1}. For NGC6946 the average of 3 observations of the reference position is $31\pm7.5\times10^{-14}$ erg s^{-1} cm^{-2} beam^{-1}. Thus the foreground Milky Way emission is greater but more uniform for NGC6946.

We calculated the total *r.m.s.* on the data measurements in NGC1313 summing in quadrature the *r.m.s* resulting from the line fitting (Tables 2 and 3) and the uncertainty on the foreground contribution derived from the dispersion of the distribution of the IRAS 100 μm flux measured around NGC1313 as described in Appendix 1 (5×10^{-14} erg s^{-1} cm^{-2} beam^{-1}). In the following analysis we will consider only those points with a [CII]

flux higher than 5 times this *r.m.s.* after foreground subtraction. The total uncertainties on the [CII] values include also the 30% calibration uncertainties.

The uncertainties for each LWS measurements in NGC6946 are the combination of the uncertainty on the line plus baseline fitting (Table 4) and the 30% calibration uncertainties. For this galaxy also, we will consider only those regions with [CII] flux higher than 5 times the *r.sm.s.* in the data (Table 2) after foreground subtraction.

Finally, the foreground corrected [CII] value was multiplied by 0.6 to take account the fact that the LWS calibration has been performed on point like sources whereas we are observing extended sources (Gry, Swinyard, Harwood et al. (2000)).

We *interpolated* the [CII] flux corrected for the foreground emission to produce maps at 158 μm for display purposes only. The [CII] contours superposed on the LW2 (5–8 μm) ISOCAM image for both galaxies are shown in Fig. 3 and briefly discussed in Sec. 4.2.

4. RESULTS

4.1. [CII] emission, dust and radiation field: comparison with the ISO–KP sample

Figure 4 shows the logarithm of the [CII]/FIR[3] and [CII]/νf_ν(5–10μm) ratios as a function of 60/100 μm IRAS colors for NGC6946 and NGC1313. These ratios are compared to the integrated emission of a sample of 60 normal galaxies presented in Malhotra et al. (2001) and Helou et al. (2001). For NGC6946 and NGC1313, only the 5σ detections at 158 μm are considered. Furthermore, since the mid–infrared (MIR) size of NGC1313 is smaller than the extent of the emission at 158 μm, for this galaxy we use only the LWS pointings included in the area detected at MIR wavelengths.

The ratios used in Fig. 4 have the following physical meanings. Assuming, as is the case here, that the [CII] flux is larger than the [OI] flux, the [CII]/FIR ratio is an indication of the efficiency of grain photoelectric heating. Grain photoelectric heating of the gas occurs when stellar photons eject energetic electrons from grains into the gas. The efficiency is defined as the ratio of the heat energy delivered to the gas by the photo electrons to the FUV photon energy delivered to the grains. [CII] and [OI] generally dominate

---

[3]Here, the FIR flux is defined as in Helou et al. ((1988)): FIR (W m^{-2})=$1.26\times10^{-14}\times(2.58\times I_{60\mu m}(\mathrm{Jy})+ I_{100\mu m}(\mathrm{Jy}))$

the cooling of gas in the regions where grains absorb the stellar photons. Therefore, if [OI] is weak, the [CII]/FIR ratio approximates the efficiency of grain photoelectric heating.

The 60/100 μm is indicative of the temperature of the grains emitting at FIR wavelengths. If these grains are in thermal equilibrium[4], their temperature is set by the intensity of the radiation field. In this condition, the 60/100 μm traces the intensity of the radiation field.

The FIR emission is mostly due to relatively large ($\sim$0.01–0.1 μm) dust grains, which absorb most of the stellar flux (see Table 2 from Dale et al. (2001)). However, the photoelectric heating efficiency of small grains is considerably higher than that of the large grains, so that the small grains disproportionately contribute to the photoelectric heating of the gas (Watson (1972), Bakes & Tielens (1994), Weingartner & Draine (1999)). The small grains and the carriers responsible for the Aromatic Features in Emission (AFEs) produce most of the emission in the 5-10 μm wavelength range. The carriers responsible for AFE are believed to be planar aromatic compounds mostly associated with Polycyclic Aromatic Hydrocarbons (”PAHs”, Puget & Lèger (1989), Allamandola, Tielens & Barker (1989)) with sizes $\lesssim$10 Å.

[4]This is true only to first order because the emission from smaller grains not in thermal equilibrium contributes to the FIR emission and it is expected to be larger in the 60 μm band in relatively low radiation field

We calculate the flux in the 5-10 μm band, νf_ν(5–10μm), by multiplying the ISOCAM LW2 (5–8.5 μm) flux by a scale factor of 1.7 (see Helou et al. (2000), (2001)).

Figure 4 shows that the [CII]/FIR ratio decreases as the radiation field increases (Malhotra et al. (2001)). On the other hand the [CII]/(νf_ν(5–10μm)) ratio is quite constant for a large range of radiation fields (Helou et al. (2001)) (stars in Fig. 4). The behaviour of the CII/FIR ratio has been interpreted as principally due to an increase of the positive charge of grains as the incident stellar flux increases, which lowers the photoelectric yield and thus the heating (and the cooling) of the gas (Malhotra et al. (2001)). Bakes & Tielens (1994), (see their Fig. 6) showed that, for a given spectrum of incident stellar flux, disk shaped grains, like the carriers responsible for the AFEs, are less ionized than spherical grains of the same size. Other than this shape effect, grain charge is fixed by the $G_0\sqrt{T}/n_e$ ratio (Hollenbach & Tielens (1999)). Here G_0 is the FUV (6–13.6 eV) ISRF normalized to the solar neighbourhood value expressed in Habing flux: 1.6×10^{-3} erg s^{-1} cm^{-2}; n_e is the electron density in the gas. The grain charge increases with the $G_0\sqrt{T}/n_e$ ratio. $G_0\sqrt{T}/n_e$ is proportional to the ratio of the UV photoejected rate of electrons from a grain surface to the recombination rate of electrons from the gas. As $G_0\sqrt{T}/n_e$ increases and all grains become more positively charged, the heating efficiency of the larger grains is reduced

more than that of the carriers responsible for the AFE and, therefore, such carriers provide an increasingly important fraction of the heating source for the gas.

The constancy of the [CII]/νf_ν(5–10μm) ratio as the radiation field increases may suggest that there exists a special connection between the carriers responsible for AFE and the photoelectric heating. Nevertheless, the nature of this connection is not yet completely understood. The fact that both the excitation of the aromatic carriers and C^+ heating are related to FUV photons is not sufficient to explain the observed MIR-[CII] relation because neither the [CII] nor the AFE are proportional to the FUV photons: the first because of the grain charging, the second because, since photons determine the charge states of the aromatic carriers, there would be proportionality between AFE and FUV photons, only if all these states had the same efficiency in converting photons into the AFE, which is unlikely. One additional complication is that the photo-electric efficiency of the aromatic carriers, as traced by the ([CII]+[OI])/AFE ratio, increases with the 60/100 μm ratio (Helou et al. (2001)), suggesting an increse of the photoelectric heating of AF carriers, rather than a decrease as expected in high heating intensity environments due to grains charging. However, this decrease may be also due to a decrease of the aromatic carriers with respect to the bigger grains, as seems to suggest the observed decreasing of the AFE/FIR

ratio with the 60/100 μm colour ratio (Helou et al. (1991)). The weak point of this scenario is that one has to invoke feedback mechanisms able to make these decreasing rates exactly the same. Helou et al. ((2001)) propose also an alternate scenario where a quiescent ISM component (the cirrus-like component as defined in Helou (1986)) dominates the observed heating/cooling at low 60/100 μm as expected, and an active component represented by the PDRs at the surface of the molecular clouds illuminated by young massive stars, gets over for high IRAS colors. This active component has high G_0/n ratio and therefore less gas heating due to the grain charge, and cools principally through [OI]. This would imply that in such ISM the aromatic carriers are depressed, as seems to be confirmed by the a AFE/FIR ratio which is lower in dense molecular clouds than in the atomic medium (Boulanger et al. (1996)).

The [CII]/FIR observations of separate regions within NGC6946 and NGC1313 as a function of 60/100 μm agree with the general trend outlined by the global [CII]/FIR ratios of the ISO–KP galaxies. Unfortunately, since there are no (LWS beam averaged) regions inside the resolved galaxies with a 60/100 μm ratio $\gtrsim 0.6$, we cannot check whether the [CII]/FIR deficiency at high 60/100 μm is still similar to the global behavior observed in more in galaxies. However, small [CII]/FIR ratios have been already observed in high radiation field sources of the Milky Way by Stacey et al. (1991). The

global averaged values of [CII]/FIR for these two galaxies agree with the ISO–KP galaxies average value. The global mean values and dispersion are: $\mathrm{Log}_{ISO--KP}$([CII]/FIR)=-2.42 σ_{ISO-KP}=0.18; Log_{N1313}([CII]/FIR)=-2.18 $\sigma_{NGC1313}$=0.25; and Log_{N6946}([CII]/FIR)=-2.29 $\sigma_{NGC6946}$=0.17.

The [CII]/νf_ν(5–10μm) ratio in the regions of NGC6946 and NGC1313 also statistically agree with the mean global ratio of the ISO–KP sample (-1.85$\pm$0.18). At the distances of these galaxies the LWS FWHM beam corresponds to a linear length $\sim$1.5 kpc. However, the mean [CII]/νf_ν(5–10μm) values for NGC1313 (-1.67$\pm$0.17) and NGC6946 and (-2.1$\pm$0.16) differ by more than one σ in dex from each other. This is also shown in the top panels of Fig. 5, where the distribution of the [CII]/FIR and [CII]/νf_ν(5–10μm), for the two nearby galaxies only, are presented. In principle, a high [CII]/νf_ν(5–10μm) ratio may be due to either a higher [CII] emission per HI atom or to a lower MIR emission per HI atom in NGC1313 than in NGC6946. Fig. 5 also shows the surface brightness distributions of the FIR (left middle panel), νf_ν(5–10μm) (right middle panel), [CII] (left bottom panel) and νf_ν(5–10μm)/FIR ratio (right bottom panel) for NGC6946 and NGC1313 only. The FIR flux distribution in NGC1313 is comparable to, if not shifted to lower values than, the FIR flux distribution in NGC6946. On the other hand, the averaged AF flux distribution in NGC1313 is significantly shifted to lower values than in NGC6946, whereas

the [CII] flux distributions are comparable. The most significant difference, however, is the νf_ν(5–10μm)/FIR ratio distribution, which is significantly lower in NGC1313 than in NGC6946. *This means that there is intrinsically less AFE in NGC1313 than in NGC6946*, even though the emission of the relatively larger grains and the gas cooling flux are comparable in the two galaxies. We furthermore note that the NGC1313 property of having [CII]/νf_ν(5–10μm) values higher than NGC6946 is also shared by the irregular galaxies of the ISO–KP sample (marked with a box in Fig. 4) and by three regions in IC10 (marked with asterisks in Fig. 4, Hunter et al. (2001)). The fact that these Irregulars may also have MIR surface brightness smaller than in normal spirals is suggested by the behavior of the 7μm/15μm colors as a function of the MIR surface brightness of NGC1313, NGC6946 and IC10 presented in Dale et al. (1999). While the shape of the three curves is the same, the surface brightness for both NGC1313 and IC10 are significantly lower than the MIR surface brightness reached by NGC6946.

What causes the AFE to be lower in NGC1313 than in NGC6946? The infrared surface brightness is proportional to the product of the dust column density and the intensity (and hardness) of the radiation field (Dale et al. (1999)). But, since the 60/100 μm ratio traces the intensity of the radiation field, and regions with the same 60/100 μm ratio have different

[CII]/νf_ν(5–10μm) ratios in NGC1313 and NGC6946, we must conclude that the column density of the carriers responsible for AFE in NGC1313 is lower than in NGC6946, either as an intrinsic property of the dust, and/or as a result of greater radiation field hardness in NGC1313 than in NGC6946, leading to the destruction of these carriers (Boulanger et al. (1988), Cesarsky et al. (1996), Contursi et al. (2000)).
MIR low resolution spectra of very metal poor dwarfs show weak AFE over large portions of the galaxies (Madden (2000)). NCG1313 is not as extreme in its metal content, as the galaxies targeted by Madden (2000), but we may be seeing the beginning of this phenomenon which becomes more and more important as the metallicity of the galaxies decreases.
Therefore, it is likely that the lower metal content in NGC1313 compared to NGC6946 accounts for the lower column density of the carriers producing the AFE observed in NGC1313. In low metallicity galaxies, [CII] shells surrounding CO cores are larger than those in normal metallicity environments (Lequeux et al. (1994)). This would translate in a I(CII)/I(CO) ratio higher in NGC1313 than in NGC6946. As we will see later (Sec. 5.3) this is indeed the case for two of three regions detected in the ^{12}CO(1–0) line in NGC1313 (Rubio et al. in preparation).

As discussed above and in Helou et al. (2001), in PDRs the carriers resposnible for AFE and small grains in general, are the most efficient

contributors to the photo-electric effect. Since the [CII]/AFE ratios in NGC1313 are greater than the values in NGC6946, NGC1313 must have a greater fraction of its [CII] emission not produced by photelectric effect on grains. This extra [CII] emission is probably arising from HII regions, as opposed to PDRs. In HII regions the gas is primarily heated by electrons from HII. Following Molhotra et al. (2001) it is possible to estimate the contribution of ionized gas to the observed [CII] emission, scaling the [NII] fine structure line measurements at 122 μm by a factor which depends on the C/N ratio. We perform the detailed calculation in § 5.1. Unfortunately, in the case of NGC1313, only three regions have been observed in the [NII(122 μm)] line, and therefore we cannot draw statistically significant conclusions. However, in at least one of these regions, the observed [CII] emission seems to arise nearly completely from diffuse ionized gas, a condition not even reached in the starburst nucleus of NGC6946. In galaxies with high fractions of [CII] arising from HII regions, the [CII]/FIR ratio does not reflect the grain photoelectric heating efficiency. Moreover, although the [CII]/FIR distribution of the regions in NGC1313 and NGC6946 and the global ratios of the ISO–KP galaxies statistically agree, the average [CII]/FIR ratio for NGC1313 is somewhat higher than for NGC6946 and, more generally, irregular galaxies tend to have higher [CII]/FIR ratios than spirals. This suggests that irregular galaxies with a greater star formation rate (SFR) per

unit surface than spirals (e.g. the Magellanic Clouds: Rubio, Lequeux & Boulanger (1993)), derive more of their [CII] emission from HII regions than spirals do.

4.2. Global [CII] emission of NGC6946 and NGC1313

4.2.1. NGC6946

The [CII] contours of the *interpolated* map of NGC6946 superposed on a LW2 (7μm) ISOCAM image (Dale et al. 2000a) are shown in Fig. 3 (top). As mentioned before, we do not use the interpolated map for the analysis but it can be useful to derive the general morphological characteristics of NGC6946 in the 158 μm emission line. As expected, the starburst nucleus is the brightest [CII] source, and a secondary peak is visible toward the north–east arms of NGC6946, which are known to be the brightest arms in Hα. A weaker enhancement in the [CII] emission is also visible around the bright MIR spots north–west from the center. Therefore, these secondary peaks presumably are related to star forming regions. In addition, an extended and diffuse emission is also present throughout the disk; its extension is comparable to the extended emission found at MIR wavelengths with ISOCAM at 6.75 μm and 15 μm. A similar decomposition in three components was previously done by Madden et al. (1993) with KAO

observations of the same galaxy.

The total [CII] luminosity of NGC6946 is 3.7×10^7 $L_\odot$. This value has been obtained by summing all the 5σ detections of NGC6946 at 158 μm and its uncertainty is dominated by the 30% calibration uncertainty of LWS. This method of calculating the total [CII] luminosity, however, is likely to underestimate the total flux, because we may be missing some flux in-between the pointings. To estimate how much flux we miss, we proceed in different ways. A first crude estimation can be done by multiplying the flux by the ratio of the area not covered by the LWS beam to the area covered by the LWS beam among adjacent pointings. This gives 17% more flux than the above value.

For a more precise estimation, we use the linear correlation between the MIR and the [CII] emission presented in Helou et al. (2001) and introduced in the previous Section.

The mean log([CII]/(ν f_ν(5–10 μm))) value for the ISO–KP galaxies is equal to -1.85 with a dispersion equal to 0.18 dex. Assuming a total flux in the LW2 filter equal to 11.19$\pm$2.24 Jy (Dale et al. (2000)) and using this mean ratio to estimate the [CII] flux, we obtain a total [CII] luminosity of 5.1×10^7 $L_\odot$ with 20% uncertainty, *i.e.* the ISOCAM integrated flux uncertainty. Comparing this value to the value found considering only the 5 σ detections in the LWS pointings, we conclude that we miss $\sim$ 30% of the

total flux. Hereafter, we will assume that the total luminosity of NGC6946 in the [CII] line emission is 5.1×10^7 $L_\odot$ with a total uncertainty equal to 20%. This value compares favourably with the $5.2\times10^7 L\odot$ [5] obtained in a similar sized map from KAO observations (Madden et al. (1993)). This value corresponds to 0.8 % of the FIR luminosity. To calculate the ratio of the [CII] luminosity to the total infrared luminosity (TIR) we follow Dale et al. (2001) who calculated TIR/FIR as a function of the 60/100 μm IRAS ratios by modelling the infrared emission of 69 normal galaxies observed by ISO and IRAS. The NGC6946 global 60/100 μm ratio is 0.46 and the corresponding TIR/FIR ratio is 2.26. Thus the [CII] luminosity is 0.35% of the total infrared luminosity.

Madden et al. (1993) decomposed the KAO map of NGC6946 in three main [CII] components: the nuclear region, the spiral arms, and an extended component (hereafter N, SA and E). We obtain a nuclear [CII] luminosity (within 75 $''$) equal to 4×10^6 $L_\odot$, 8 % of the total flux. Madden et al. (1993) found a luminosity equal to 2.9×10^6 $L_\odot$ in the central 60$''$, which is 6% of

[5] The luminosity values published in other papers are calculated assuming a distance for NGC6946 different from 4.5 Mpc. Therefore, we give here the corresponding values scaled for the distance of 4.5 Mpc, assumed in this paper.

the total [CII] luminosity measured with KAO. However, these two values agree within the LWS and KAO uncertainties. In fact, we expect the nuclear value calculated from the KAO data to be somewhat smaller because the authors integrated the [CII] flux over a solid angle ∼45% smaller than the LWS beam.

Since we cannot use the interpolated map for our analysis, we cannot easily separate the [CII] emission associated with the spiral arms and the extended emission. Madden et al. (1993) compared the KAO [CII], FIR, CO and HI emission along a east-west cut of NGC6946. They found the [CII] emission in the disk of NGC6946 a factor ~ 2 higher than in the nuclear region when scaled to the FIR and CO emission. They interpreted this as due to an extended [CII] component which accounts for 70% of the total emission. In Fig. 6 we show a similar comparison. Since we cannot use the interpolated map to calculate the emission along one given direction, in order to include as many LWS pointings as possible, we perform two cuts with P.A. equal to 45° and 135° respectively (see Fig. 1). We do not find any significant excess of the [CII] emission as in Madden et al. (1993). However, we have fewer points than Madden et al. (1993) due to the larger LWS beam.
Therefore, we try to estimate more precisely the amount of diffuse [CII] emission as follows. Madden et al. (1993) found that the [CII] surface brightness for the extended emission in NGC6946 ranged from 1 to 2 $\times 10^{-5}$

erg s^{-1} cm^{-2} sr^{-1}. The minimum and maximum [CII] surface brightness detected with LWS and corrected for the foreground emission are 3.6×10^{-7} (reg. 7 in Table 4; not a 5 σ detection) and 4×10^{-5} erg s^{-1} cm^{-2} sr^{-1} respectively (reg. 31 in Table 4). The surface brightness values for the extended emission given by Madden et al. (1993), are ~30 times higher than the minimum surface brightness detected with LWS at 158 μm. All but two (one of which is the nucleus) of the LWS 5 σ measurements, have surface brightness lower than 2×10^{-5} erg s^{-1} cm^{-2} sr^{-1}. This suggests that this value is too high to arise principally in the diffuse low density gas. However, if we consider 1×10^{-5} erg s^{-1} cm^{-2} sr^{-1} as maximum emission for the diffuse component, we find that it contributes $\sim$ 35% of the total [CII] emission.

We can estimate the minimum contribution of the [CII] extended component to the total [CII] emission in NGC6946 by simply assuming that the [CII] extended component is uniformly distributed over the galaxy disk with a surface brightness corresponding to the minimum [CII] flux we have detected ($> 5\ \sigma$) in NGC6946. This value, corrected for the foreground emission, is 1.3×10^{-6} erg s^{-1} cm^{-2} sr^{-1} and corresponds to region 27 of Table 2. Integrating this value over the optical size of NGC6946 (see Table 1), we obtain a total diffuse [CII] minimum contribution equal to 7.6×10^{6} $L_\odot$, 15% of the total [CII] luminosity. Using the [CII]/(ν f_ν(5–10 μm)) relation we find that this minimum [CII] surface brightness corresponds to a LW2 surface

brightness equal to 0.17 MJy sr^{-1}. Note that the typical surface brightness of quiescent regions of the Milky Way like the high galactic clouds, with an average HI column density of 2–3 $\times 10^{20}$ cm^{-2} is $\sim$ 0.04 MJy sr^{-1} (Dale et al. (2000)).

It is more likely that the [CII] diffuse component is not uniform and that it might decrease with galactocentric distance. Following this line of thought, we can set an upper limit to the diffuse [CII] component using the [CII]/(ν fν(5–10 μm)) correlation. We divide the ISOCAM LW2 image in concentric rings of 15$''$ width, *i.e* $\sim$ twice the ISOCAM resolution at 7 μm, and assume that the [CII] diffuse component in each ring is uniform with a [CII] surface brightness corresponding to the minimum LW2 surface brightness observed in each ring. Summing up all these components we find that the maximum [CII] extended contribution is equal to 1.8$\times 10^7$ L$\odot$ which is 37 % of the total [CII] flux.

In conclusion, we found that the diffuse [CII] emission contribution to the total flux is much smaller ($\lesssim$ 40%) than the value found by Madden et al. (1993). We note that our value agrees with that found by Sauty Gerin & Casoli (1998) who, through radiative transfer modelling of NGC6946, estimate the diffuse extended component at 30% of the total [CII] emission. The discrepancy between this and Madden et al. (1993) work may arise from the fact that the background emission in the NGC6946 direction is much

better determined with the LWS observations than with the KAO data, for which no specific observations of reference positions were performed. This may explain why the KAO data are systematically higher than the LWS measurements. In fact, if we assume as typical diffuse [CII] surface brightness the upper limit value given in Madden et al. (1993) equal to 2×10^{-5} erg s^{-1} cm^{-2} sr^{-1}, and we assume the diffuse component to be uniformly distributed over the optical size of NGC6946, we find a diffuse contribution to the total emission $\sim$2×35%, which is close to what these authors found.

4.2.2. NGC1313

Fig. 3 (bottom) shows the [CII] contours of NGC1313 superposed on a 6.75 μm ISOCAM image (Dale et al. (2000)). As in the case of NGC6946 we use the interpolated [CII] map only for general morphological investigation and for display purposes. This map has been obtained considering only the 5σ detections where the σ associated with each pointing has been calculated as described in Sec. 3. There is bright [CII] emission associated with bright infrared emission, corresponding to the center, the bar and the HII regions of the galaxy. These regions are visible as an S-shaped morphology in the figure. Three peaks are visible, two in the northern and one in the southern arm. There is also diffuse emission which smoothly decreases towards the

outer disk.

The total [CII] luminosity is 9×10^6 $L_\odot$, a factor 5 less than the NGC6946 luminosity. As in the case of NGC6946, this value has been obtained summing all the 5σ detections. If we account for the missing flux by correcting for the area in-between the beam, we obtain a luminosity equal to 1.05×10^7 $L\odot$, 15% more than the previous value. Unfortunately we cannot use the [CII]/νf_ν(5–10 μm) ratio to better estimate the true total [CII] luminosity of NGC1313 because the MIR extension of this galaxy is smaller than the size of the [CII] emission (see Fig. 1 top panel). Therefore, we will take our value for the total [CII] luminosity as a lower limit. The $L_{[CII]}/L_{FIR}$ ratio is $> 0.5\%$, comparable with what we obtain for NGC6946. Also the IRAS 60/100 μm colors for the two galaxies are exactly the same, giving the same TIR/FIR ratio and thus a value of 0.2% for the $L_{[CII]}/L_{TIR}$ ratio.

NGC1313 does not have classic spiral arms or a classic nuclear region and therefore it is very difficult to separate the [CII] contribution from different galaxy components even using other observations than the 158 μm measurements to identify these components. Its 6.75 μm ISOCAM image does show a diffuse, low surface brightness emission, which ranges from 0.06 to 0.1 MJy/sr. These values are comparable to the typical surface brightness at 6.75 μm of cirrus in our and external galaxies (Dale et al. (2000)). The

corresponding [CII] surface brightness calculated through the [CII]/νf_ν(5–10 μm) relation corresponds to 7×10^{-7} – 1×10^{-6} erg s^{-1} cm^{-2} sr^{-1}. We note that the [CII] lowest surface brightness (foreground subtracted) detected with LWS (even if this is not a 5σ detection) is 7.8 $\times10^{-7}$ erg s^{-1} cm^{-2} sr^{-1}, and it falls in this range. Thus if we assume that a uniformly diffuse low surface brightness emission between 7×10^{-7} – 1×10^{-6} erg s^{-1} cm^{-2} sr^{-1} is present over the galaxy's entire optical disk, this would contribute 20–30 % to the total [CII] emission.

5. Discussion

The [CII] 158μm, [OI] 63μm and FIR continuum observations can be used to constrain the density, far ultraviolet (FUV) flux, temperature, thermal pressure and other properties of the neutral interstellar gas in galaxies (e.g. Kaufman et al. 1999). In order to analyze the emission from neutral gas, we first have to remove the contribution of ionized gas to [CII] emission, which is done by scaling the [CII] emission from HII regions with the [NII] 122μm emission from these regions (§5.1). In §5.2, we apply PDR models to the emission from neutral media. In §5.3, we discuss the relationship of [CII]–emitting gas with the neutral gas responsible for CO and HI emission, and in §5.4 we assess the relative contributions of dense and diffuse neutral gas to the observed HI emission.

5.1. [CII] emission from neutral and ionized gas

[CII] emission can arise both from neutral (PDR) gas and from ionized (HII) gas. In order to compare our observations to the PDR models, we must first attempt to remove the [CII] emitted from ionized gas. Following Malhotra et al. (2001), we can estimate the [CII] emission from ionized gas by comparing it with [NII] 122μm emission. [NII] only arises from ionized gas since nitrogen has an ionization potential of 14.5 eV. Given the gas phase abundance ratio of carbon to nitrogen, C/N, we can estimate the [CII] emission from HII regions by an appropriate scaling of the [NII] emission. Absorption line studies of diffuse interstellar gas in the Milky Way (Sofia et al. (1997), Meyer et al. (1997)) find $(C/N)_{diffuse} = 1.9$. In dense ionized regions, Rubin et al. (1988),(1993) find an abundance ratio $(C/N)_{dense} = 3.8$. This abundance ratio has been shown to be independent of metallicity in both normal and irregular galaxies (Garnett et al. (1999)), so we adopt the Milky Way diffuse and dense gas values for NGC6946 and NGC1313. With these abundance ratios, the [CII] intensity is 5.8 times the [NII] intensity if the emission is from the Diffuse Ionized Medium (DIM); the [CII] intensity is 1.1 times the [NII] intensity if the emission is from dense HII regions. In NGC6946, the observed [CII]/[NII] flux ratio is > 7.7 in all regions where both lines were observed. In NGC1313, there are only upper limits on this ratio (Figure 11), > 4 in one location and > 10 in the two others. If

the [NII] emission arises only from dense ionized gas, then very little of a galaxy's overall [CII] emission comes from ionized gas; if the [NII] emission comes only from diffuse gas, then ionized gas contributes considerably to the integrated [CII] emission. Most ($\sim 70\%$) of the [NII] 122μm emission from the Milky Way comes from the DIM (Heiles (1994)). If we assume that 70% of the of the [NII] emission from NGC6946 and NGC1313 comes from diffuse ionized gas, then a conversion factor [CII]/[NII] = $0.7([CII]/[NII])_{diffuse} + 0.3([CII]/[NII])_{dense}$=4.3 is appropriate. However, in the next section, we explore the range of PDR conditions possible when assuming either that the [NII] emission is entirely from diffuse ionized (DIM) or entirely from dense ionized (HII) gas. In NGC6946, 12 regions were observed in both [CII] 158μm and [NII] 122μm emission, resulting in 11 [NII] detections and one upper limit. In NGC1313, 3 regions were observed in both lines, but only upper limits were found for [NII]; for these regions, we correct the [CII] emission based on the upper limits, so our results are less certain than for NGC6946.

5.2. Comparison with the PDR models

In order to further constrain the interstellar medium conditions in NGC6946 and NGC1313, we compare the observed infrared line and continuum emission with the PDR models of Kaufman et al. (1999). These models

allow for the determination of the average gas density, n, the surface temperature of the emitting gas T_s, and the average far-ultraviolet (FUV) flux, G_0, illuminating the interstellar gas, where G_0 is measured in units of the Habing (1968) value for the average solar-neighbourhood FUV flux, $1.6 \times 10^{-3}\,\mathrm{erg\,cm^{-2}\,s^{-1}}$. The most commonly used diagnostics are the ratio of intensities in the main neutral gas coolants, [CII] 158μm/[OI] 63μm, along with the line-to-FIR continuum ratio, ([CII] 158μm + [OI] 63μm)/FIR. The use of ratios eliminates the beam area filling factor as a parameter, assuming the [CII], [OI] and FIR emission come from the same clouds, and allows derivation of $\mathrm{G_0}$ and n.

The Kaufman et al. models were developed for comparison with relatively nearby Galactic star forming regions, where PDR gas is illuminated from one side by hot stars. However, these ISO observations involve beams which cover a galaxy region of size $\sim 1.5\,\mathrm{kpc}$. The observed line emission from this large region arises from an ensemble of clouds with random orientations. As a result, it is appropriate to modify the model results so as to approximate the emission from clouds illuminated on all sides. The models show that [OI] 63μm is typically optically thick, while [CII] 158μm and the FIR continuum are optically thin. As a result, a spherical cloud will emit [CII] and continuum radiation from both the side facing the observer and the far side of the cloud, while [OI] emission comes only from the side facing

the observer. We have modified the Kaufman et al. models to account for illumination from all sides [6], and we use these modified results to find the gas density and FUV flux in each of our pointings. Figure 7 shows the pointing and beam sizes in NGC6946. Since our observations are averages over the ISM in each beam, the results for n and G_0 that we derive are intensity weighted averages over the beam. Comparing the observed [CII] intensity with that predicted by the models for the derived G_0 and n gives the area filling factor of the emitting regions, $\Phi_A = I[CII]_{observed}/I[CII]_{predicted}$ (Wolfire et al. 1995).

Since we are dealing with regions inside NGC6946 and NGC1313, we

---

[6] We reduced by a factor of two the model prediction or, inversely, doubled the observed [OI] value. The total infrared emission has been calculated from the FIR as explained in Sec. 4.2.1 and 4.2.2. However, the PDR model assumes that only photons with energy between 6 and 13 eV ionize grains leading to gas heating. On the other hand, dust heating occurs by FUV photons and by photons with hν < 6 eV. In order to compare observations and model prediction we have to divide the TIR by a factor of two, since the observed TIR includes heating by photons of hν< 6 eV, but models do not. Therefore, we apply the model prediction with $([\mathrm{OI}]_{model} \times \frac{1}{2})/[CII]_{model}$ and $([\mathrm{OI}]_{model}+ 2\times[\mathrm{CII}]_{model})/(2\times\mathrm{TIR}_{model})$ ratios.

do not know *a priori* which of the two components of the ionized gas dominates the [NII] emission. We expect different contributions depending on which component of the galaxy (nucleus, spiral arms, diffuse disk) is located in our beam. We therefore derive values of G_0 and n obtained upon removing the ionized gas contribution to [CII] emission assuming [CII] arises only from the DIM or only from dense HII regions. The results for both galaxies in these two limits are listed in Tables 5 and 6. The percentage of [CII] emission arising in ionized gas (Col. 6) is comparable for regions in NGC6946 and NGC1313. Only one region in NGC1313 (reg. 91) has a very high contribution to the observed [CII] emission arising in ionized gas: for exemple, in this region, when one considers the DIM contribution, all the observed [CII] emission seems to arise in ionized medium. It is worth mentioning that this same region of NGC1313, has not been detected in CO(1–0) though its [CII] emission is comparable to the emission of reg. 69, where the highest CO content has been observed (§5.3.1).

Figure 7 shows a comparison between the G_0 and n values (Col. 2 and 3 in Tables 5 and 6) obtained in NGC6946 and NGC1313 with those obtained for the ISO–KP sample (Malhotra et al. (2001)). For NGC6946 and NGC1313, we only show the case in which the [CII] observed fluxes have been corrected for the contribution from DIM, the same correction applied to the ISO–KP normal galaxy sample. We also plot the point corresponding to G_0 and n

obtained upon averaging the [CII], [OI] and FIR emission over the NGC6946 disk. The solutions show that conditions in regions inside NGC6946 are similar to those in the ISO–KP galaxy sample, although none of the regions observed here match the highest G_0, n solutions in the ISO–KP sample. In the ISO-KP sample, all of the emission from a galaxy fit in an single beam. We might have expected the conditions in isolated regions of our two galaxies to be more extreme than the galaxy averages from the ISO-KP sample. The LWS beam is, however, large enough (∼1.5 kpc at NGC6946 and NGC1313) that we are still averaging over many PDR components. The fact that our results for G_0 and n are systematically lower than the largest values found in the ISO-KP sample may be telling us that emission from the distant sample galaxies is dominated by a few massive star forming regions, perhaps from each galaxy nucleus.

Comparing the values given in Tables 5 for NGC6946, we note that all but regions 33 and 45 have comparable gas volume densities but different $\frac{G_0}{n}$ values, meaning that what principally drives the differences inside this galaxy is a change in the FUV flux illuminating the clouds in the LWS beam rather than density variations.

We now to compare the PDR model results to the MIR emission properties in NGC6946. Figure 8 shows the regions for which we obtained model solutions in NGC6946 overlayed on an ISOCAM image at 7 μm. Most of

the regions with the lowest (<0.2) $\frac{G_0}{n}$ values (15, 33, 40, 43 and 47), are also those not or partially related to bright spots at mid infrared (MIR) wavelengths. Thus it is likely that in these regions, the contribution of an active component to the total MIR emission is lower than in the rest of the galaxy indicating that, to first order bright MIR spots corresponds to warmer PDRs as expected. However, since the MIR emission is proportional to the product of dust (and therefore gas) column density and the intensity of the radiation field, its relation with the $\frac{G_0}{n}$ ratio is not straightforward. This is clearily shown by the example of region 45, which has the highest $\frac{G_0}{n}$ value but it does not correspond to any bright MIR emission. In this case the high $\frac{G_0}{n}$ value is due to a very low gas volume density and a moderate G_0. On the contrary, bright MIR regions as region 47, can have a low $\frac{G_0}{n}$ value. In conclusion, to first order, MIR bright emission does correspond to warm and dense PDRs but this is not a one to one correspondence.

The [CII] intensities from neutral gas in two modeled regions in NGC1313 are lower limits, since the contribution from diffuse ionized gas to the total [CII] emission has been scaled from the upper limits in the [NII] line. Their $\frac{G_0}{n}$ values are comparable to the lowest found in the disk of NGC6946. All these regions correspond to bright MIR emission.

5.3. Relationship between [CII], CO and HI emission

[CII], CO and HI emission generally originate in PDRs. HI and [CII] are generated in diffuse clouds and from the surfaces of molecular clouds, with [CII] being less sensitive to the low density ($n \ll 10^3\,\mathrm{cm}^{-3}$) components; CO emission arises from deeper into PDRs, where molecules are shielded from dissociating radiation but where FUV photons still dominate the heating and/or dissociation of other oxygen–bearing molecules. In this section, we attempt to determine to what extent the [CII], HI and CO emitting gases are physically related in our galaxies.

Figure 6 already gives an indication of the origins of these lines in NGC6946. [CII], CO and the FIR all scale closely, peaking toward the center of the galaxy and falling off considerably in the outer regions. HI 21 cm emission, however, remains quite constant in intensity over the mapped area. HI 21 cm emission is sensitive neither to density nor temperature, but only to the column density of HI. [CII] emission increases sharply with density, to $n \sim n_{crit} \sim 3 \times 10^3\,\mathrm{cm}^{-3}$ and with temperature, to $T \sim \Delta E/k \sim 92$ K. CO $J = 1 - 0$ emission tends to be optically thick, and is therefore mainly dependent on the area filling factor of molecular clouds, with a rather weak dependence on G_0 or n (Kaufman et al. 1999). The impression given by Figure 6 is that since CO tracks the molecular gas, and since the molecular

gas is where the star form that power the FIR emission, the CO correlates with the FIR. The [CII] tracks this dense component, as if the [CII] originates on the surfaces of the molecular clouds. As we will see in §5.3.1 below, there are good theoretical reasons to expect this *spatial* correlation.

Fig. 9 shows [CII] intensities versus ^{12}CO(1-0) intensities for regions in NGC6946 and NGC1313, and it compares these with the Stacey et al. (1991) galaxy sample, as well as the ISO–KP galaxies for which ^{12}CO(1–0) data are available (Lord et al. in preparation). The CO data for NGC6946 are from a ^{12}CO(1-0) map kindly provided by M.D. Thornley, T. Helfer and M. Regan from the BIMA Survey on Normal Galaxies (SONG) sample. It covers about $6.5' \times 6.5'$ and the CO intensities averaged over the LWS beam for those regions included in this area are listed in Table 8. Also plotted are three regions of NGC1313 for which ^{12}CO(1-0) data were taken at SEST in November 2000. Since the SEST beam at 115 GHz is much smaller ($40''$) than the LWS beam at 158 μm, we observed three positions inside each LWS beam (spaced at $\frac{1}{2}$ the FHWM of the SEST beam) to try to estimate the average surface brightness in the LWS beam (Rubio et al. in preparation). These averaged intensities are listed in Table 8.

Fig. 10 shows the relationship between the deprojected[7] [CII] surface

[7]The inclination angles assumed for NGC6946 and NGC1313 are 30° and

brightness and the deprojected HI column density, calculated in the optically thin limit, for each region in which we have a 5σ [CII] detection. We also plot curves representing the intercloud medium (n$\sim$0.1 cm^{-3} and T=10^4 K), standard HI clouds (n$\sim$30 cm^{-3} and T$\sim$100 K assuming an area filling factor equal to unity) and for cirrus emission in our galaxy (Bennett et al. (1994)). The dependence on n arises mainly because the HI is in *Local Thermodynamic Equilibrium* (LTE) even at the lowest interstellar densities, whereas the critical density for the [CII] transition is about 3×10^3 cm^{-3}. The HI data are from Boulanger & Viallefond (1992) and Ryder et al. (1995) for NGC6946 and NGC1313 respectively. The horizontal dashed lines correspond to the [CII] intensities found by Madden et al. (1993) for three components in NGC6946. Also plotted in the same figure are galaxies observed with the KAO and presented by Stacey et al. (1991). The KAO data have a FWHM beam equal to 55$''$, and Stacey looked at the nucleus of each galaxy, so those results are biased toward the highest [CII] surface brightness. This explains why the squares in Fig. 9 are generally well above the individual measurements inside NGC1313 and NGC6946. We note, however, that the Stacey et al. (1991) deprojected surface brightness value for the nuclear region of NGC6946 agrees with the nuclear value from the present work to within the errors.

48° respectively

5.3.1. [CII] emission and the molecular gas

Stacey et al. (1991) established observationally that [CII] intensity increases linearly with CO intensity for galaxies of similar type, and that the $I_{[CII]}/I_{CO}$ ratio increases with the global star formation activity of galaxies, as measured by dust temperature. In particular, galaxies with warm dust ($T_{dust} > 40$ K) have mean $I_{[CII]}/I_{CO}$ ratios of $\sim$4200, while galaxies with relatively cold dust ($T_{dust} < 40$ K) dust have mean $I_{[CII]}/I_{CO}$ ratios of $\sim$1300. Moreover, the correlation of $I_{[CII]}$ with I_{CO} followed by galaxies with warm dust agrees very well with that traced by Galactic star forming regions and shows much less scatter than the correlation followed by cooler galaxies. Wolfire et al. (1995) showed in model calculations that this correlation arises naturally in PDRs, where [CII] emission comes from warm PDR surface layers while CO emission comes from cooler UV-shielded gas deeper into PDRs. Kaufman et al. (1999) extended these theoretical calculations to the case of low metallicity galaxies.

The [CII]–CO correlation holds for regions inside NGC6946 and NGC1313. In particular, the sequence traced by NGC6946 agrees with that of the ISO–KP sample of normal galaxies. We note, however, that the mean $I_{[CII]}/I_{CO}$ ratio for the regions inside NGC6946 is lower (~ 550) than the mean value found by Stacey for the normal spirals in their sample, while

most of the ISO–KP galaxies agree with the measurements of regions in NGC6946. This difference can be explained by the fact that the flux in the Stacey et al. (1991) sample comes principally from the 55″ central region of the galaxies whereas the ISO–KP sample data refer to the integrated emission of the galaxies (Malhotra et al. (2001)). The Stacey et al. (1991) sample is biased towards more active regions, even when the galaxies are relatively cool, normal galaxies. The integrated flux of the ISO–KP galaxy sample (Tables 4 and 7) and the regions inside the disk of NGC6946 are likely to come from a mixture of star forming and more quiescent regions.

Among the three regions observed and detected in NGC1313 in CO at 115 GHz, only one (region 69 in Tables 2 and 8) has a $I_{[CII]}/I_{CO}$ ratio in agreement with the mean value found in NGC6946 and for the ISO–KP galaxies. The other two regions have much higher $I_{[CII]}/I_{CO}$ ratios, similar to the ratio found in more active galaxies and galactic star forming regions. However, although the [CII] intensity of these two regions is high compared to other point in this galaxy, the [CII] intensities are low compared to most active galaxies and star forming regions. The CO intensity is exceptionally low, leading to the high [CII]/CO ratios. Even more telling is that the dust temperatures, as measured by the 60μm/100μm ratio, are low. Therefore, the high [CII]/CO ratios in NGC1313 likely have a completely different explanation than the fact that they arise in active star forming regions.

We propose that in NGC1313, the high ratio is explained by [CII] emission arising from low extinction diffuse gas, where penetration by FUV photons prevents the formation of CO. The low metallicity of NGC1313 may contribute to this effect, by lowering the dust extinction. In low metallicity environments, CO molecular clouds can be smaller and surrounded by large CII envelopes (Lequeux et al. (1994), Pak et al. (1998), Kaufman et al. (1999)), resulting in large [CII]/CO ratios. It is in fact this scenario which is used to explain the very high [CII]/CO intensity ratio seen in 30 Dor (see Fig. 11 of Kaufman et al. 1999).

What then explains the lower $I_{[CII]}/I_{CO}$ ratio in the one beam out of three? One possibility is that there is a significant variation of metal content within NGC1313: region n.69 may have an higher metal content than regions 89 and 90. This explanation is unlikely because no such metallicity variation has been observed in previous studies (Mollá & Roy (1999)). Another possible explanation is that it is not metallicity which drives the observed differences in the [CII]/CO ratios but the total hydrogen column densities of the clouds. Kaufman et al. (1999) discussed this point in detail. A cloud in a low metallicity environment may have a thin [CII] shell surrounding a large CO core, resulting in [CII]/CO ratios comparable to those observed in normal metallicity environments, if A_V through the cloud has the typical value of normal metallicity clouds ($A_V \sim$5-10) in our Galaxy. In other words,

the observations are consistent with the clouds in the beam (reg. 69) having higher columns on average than the clouds in the beams of regions 89 and 90. However, the total *beam-averaged* hydrogen nucleus column densities, N(HI)+2×N(H_2), are all comparable in the three regions (Table 9). This then implies that there are fewer clouds in the beam of region 69 than in the beams of regions 89 and 90, so that the individual clouds columns in region 69 are higher than in regions 89 and 90, even though the beam-average column of the ensemble of clouds is similar in all three regions.

An other interesting conclusion is that the physical conditions in NGC1313 seem to be much more inhomogeneous than those in the disk of NGC6946. Regions 69 and 91 have comparable [CII] emission but very different molecular content: region 91 has not been detected at SEST. Regions 89 and 90 have the highest [CII] emission and very little molecular gas. The [CII]/CO ratio decreases along the S-shape region outlined by star-forming regions in NGC1313, going from the south to north-east. Wells et al. (1995) also reported gradients along this region, with each of infrared-to-radio, infrared excess, and 60-to-100μm color decreasing. This could reflect differences in the star formation properties along the spiral arms of the galaxy, or as suggested by Wells et al. (1995) a decreasing dust-to-gas ratio. A more detailed analysis on this issue, which is beyond the aim of this paper, requires further CO observations and a comparison with the star-formation

properties of the different regions inside NGC1313.

5.3.2. The [CII] emission and the HI gas

In general, we would expect a correlation between HI and [CII] if both arises in PDRs. However, as discussed in the introduction, there are basically two types of PDRs which contribute significantly to neutral emission from a galaxy: low density diffuse gas illuminated by the general ISRF ($G_0 \sim 1$) and the dense ($n \gtrsim n_{crit}$) and warm ($G_0 \gg 1$) surfaces of UV illuminated Giant Molecular Clouds (GMCs). Thus, we would only expect a correlation between [CII] and HI if the bulk of the emission from an observed region comes from the same type of PDR, or the same admixture of phases.

Figure 10 shows that in NGC6946 the [CII] intensity spans more than one order of magnitude regardless of the HI intensity (or column density if the emission is optically thin). The absence of a correlation can arise if one or more of the following conditions are satisfied:

1) If most of the HI in the LWS beam is optically thick, we are underestimating the HI column density; the HI column may vary but produce relatively constant HI intensity. As the total column increased, the [CII] intensity would increase, but the HI intensity would remain at a value corresponding to the emission from optically thin gas with a column given

by HI optical depth of order unity. The average HI column density, based on the assumption of optically thin emission, of regions in NGC6946 with [CII] intensities higher than the intensity expected from standard HI clouds, is $\sim 7\times10^{20}$ cm^{-2}. The HI opacity is given by:

$$\tau_{HI} = \frac{N(HI)}{1.83 \times 10^{18} T \Delta v_5}, \tag{2}$$

where, Δv_5 is the FWHM of the line at 21 cm from a single cloud in units of km s^{-1}, and N(HI) is in units of cm^{-2} for a single cloud. The HI lines in NGC6946 are broader than $\sim$ 8 km s^{-1} (Boulanger & Viallefond (1992)). If the emission arises from a single cloud which fills the beam, this value, the observed HI column, and an estimated temperature of about 50 K[8] results in a value of $\tau \sim 1$. However, it is more likely that the beam encompasses a number of clouds. Individual clouds in the Milky Way have smaller velocity dispersions, $\Delta v \approx 2$ km s^{-1}. It would take a minimum of 4 of such clouds to produce the observed FWHM of the line of 8 km s^{-1}. If each cloud filled the beam, each cloud could only contribute to the "observed column"

[8]Boulanger & Viallefond ((1992)) found temperatures of the HI clouds in 4 annuli centered on the galaxy lower than 50 K. But these values represent the average on a much larger area than the LWS beam. Note also that the typical temperatures at the surface of the PDRs found applying the model to our observations are much higher than 50 K.

about 1.75×10^{20} cm^{-2}. Again, using the FWHM from a single cloud and the "observed column" of a single cloud, along with a temperature of 50 K, results in $\tau \sim 1$. Therefore, if these presumably diffuse clouds have temperatures close to 50 K, it is consistent that there may be a very large total column in the clouds to make the HI line very optically thick, and saturate the HI emission at a level consistent with the assumed optically thin column of 7×10^{20} cm^{-2}. However, if the temperature is higher than about 50 K, the only way for this scenario to work is to have the clouds only partially fill the beam. This is highly unlikely to explain the observations, since a large number of observations at different points all gave the same HI intensity; this would require the same beam filling factor in each beam.

Can optically thick HI clouds produce the observed wide range in [CII] intensity? The [CII] emission scales linearly with column density only if conditions are *effectively* optically thin; once [CII] emission is effectively thick, the intensity saturates at the blackbody value, increasing only logarithmically with column as the line broadens. The optical depth of the [CII] line is (Crawford et al. (1985)):

$$\begin{aligned} \tau_{[CII]} &= 0.37\left[\left(1+\frac{n_{crit}}{n}\right)e^{(92/T)}-1\right] \\ &\times\left(\frac{2e^{(-92/T)}}{1+2e^{(-92/T)}+n_{crit}/n}\right)x(C)_{-4}N(HI)_{21}\Delta v_5^{-1}, \end{aligned} \tag{3}$$

and

$$\tau_{eff[\mathrm{CII}]} \approx \tau_{[\mathrm{CII}]} \left[\frac{1}{1 + n_{crit}/n} \right], \tag{4}$$

where N(HI)=10^{21}N(HI)$_{21}$ cm^{-2} is the column density of hydrogen nuclei associated with the [CII] emission, and x(C)=$10^{-4}x$(C)$_{-4}$ is the abundance of carbon relative to H nuclei. For $n \gtrsim n_{cr}$ and $x(C)_{-4} = 1.4$, $\tau_{CII} = 1$ for an HI column density $\sim 1.5 \times 10^{21}$ cm^{-2}. Therefore, in these conditions, once the HI intensity has saturated we would expect I[CII] in NGC6946 to increase only by a factor $1.5{\times}10^{21}/7{\times}10^{20} \sim 2$ before the [CII] line also becomes optically thick and saturates. On the other hand, if $n \lesssim 0.1 n_{cr} \approx 3 \times 10^2$ cm^{-3}, the [CII] line remains effectively thin up to hydrogen columns $\gtrsim 10^{22}$ cm^{-2}, and the observed range of [CII] intensity with similar HI intensity could be reproduced. However, this would require at positions with the highest [CII] intensities columns $N(HI) \gtrsim 10^{22}$ cm^{-2}, through the disk of NGC6946, much greater than columns through the Milky Way. In addition, it does not directly explain why [CII] spatially correlates with CO and the FIR continuum but not with HI (Figure 6).

2) Another possibility is that [CII] emission arises mostly from HII regions, while the HI emission comes from diffuse neutral gas. If this were the case, then as the [CII]-to-[NII] ratio decreases and approaches the value predicted for ionized gas ([CII]/[NII]~ 0.25 for dense HII regions and ~ 4.3 for diffuse ionized gas) the [CII]-to-HI ratio should increase. In Figure 11, we show

that in NGC6946, as [CII]/[NII] decreases [CII]/HI increases, i.e. as more of the [CII] comes from ionized gas there appears to be more [CII] relative to HI. However, in the regions with exceptionally high [CII]/HI, this scenario would predict [CII]/[NII]$\lesssim$ 4.3, whereas the observations show the ratio never dropping below ~ 8 in NGC6946.

3) If the bulk of [CII] in most of the observed regions in NGC6946 comes from PDRs associated with dense gas but the bulk of HI comes from the diffuse neutral gas component, [CII] and N(HI) should not be correlated. This is consistent with the spatial anticorrelation of [CII] and HI shown in Figure 6. This suggests that HI comes from a diffuse component ($n \lesssim 10^3\,\mathrm{cm}^{-3}$) which produces insignificant [CII] emission, whereas the [CII] emission arises from a dense neutral component that produces insignificant average HI column in the beam. The dense component which produces [CII] should also produce the bulk of the CO and a significant amount of FIR emission. As we have shown in the previous Section and in Fig. 9, this is exactly what we observe in NGC6946. Moreover, as we will discuss in §5.4, the HI produced in dense ($n \gg n_{crit}$) gas associated with star forming regions, *i.e* dense PDRs, is only a few % of the total HI, and its amount does not vary significantly among the observed regions in the disk of NGC6946.

This last scenario is the most likely: the increase of [CII] observed in NGC6946 (Fig. 9) is due to dense PDRs related to star forming regions,

with a possible small contribution from the ionized gas associated with these star forming regions. This view is supported by the spatial cuts in Figure 6, which show that that HI and [CII] do not track across the plane of NGC6946. This is also corroborated by the PDR modelling results shown in Figure 7, indicating that the [CII], [OI] and FIR emission is fit by PDR gas with densities $\gtrsim 10^3\,\mathrm{cm}^{-3}$.

The situation is not as clear in NGC1313. Here there is a gradual rise in [CII] intensity with increasing HI column up to $N(HI) \sim 10^{21}\,\mathrm{cm}^{-2}$, consistent with HI and [CII] being correlated. Above $N(HI) \sim 10^{21}\,\mathrm{cm}^{-2}$, the [CII] intensity rises by a factor ~ 7, not an unreasonable amount if the [CII] emission remains effectively thin when the HI 21 cm line goes optically thick. Thus, a significant amount of the [CII] from NGC1313 could be coming from diffuse neutral gas. The fact that [CII] emission does not seem to go optically thick until higher columns of HI than in NGC6946 may also be due to low metallicity in NGC1313 (see Kaufman et al. 1999). Unfortunately, there is insufficient data to spatially correlate CO and [CII] in NGC1313 as we have done in NGC6946. If the same correlation exists in NGC1313 as in NGC6946, it would be powerful evidence that [CII] arises from the dense PDR surfaces of the CO clouds. We note that Wolfire et al. (1995) showed that for reasonable interstellar cloud masses and size distributions, dense clouds will dominate the [CII] emission, a result reinforced by the correlation

of [CII] and CO in many galaxies. Lacking this evidence, however, we must consider whether [CII] might arise mainly from diffuse gas in NGC1313.

For the regions with low [CII] intensities we point out that the HI interferometric data fail to detect low surface brightness extended emission. Comparing the NGC1313 HI total flux taken with the Australia Telescope Compact Array (ATCA) and the Parkes 64m telescope, Ryder et al. (1995) found that 6% of the total flux is lost with the interferometric observations. If we assume that most of this missing flux comes from low surface brightness extended emission in NGC1313, we conclude that the points in Fig. 9 with the lower HI column density are probably underestimates. If we distribute this excess equally to those regions with $N(HI) < 10^{21}\,\mathrm{cm}^{-2}$, the points in Fig. 9 between 10^{20} and 10^{21} cm^{-2} move up to between 5×10^{20} and 1.3×10^{21} cm^{-2}. This makes the [CII]/HI points in NGC1313 move closer to the emission expected from low density (n$\sim$30 cm^{-3}) HI clouds. We conclude that in NGC1313 we successfully observe [CII] emission from two separate ISM components. The first is associated with diffuse, low density ($30 < \mathrm{n} < 100$ cm^{-3}) atomic gas probably illuminated by the general FUV ISRF (standard atomic clouds), dominated by HI and contributing up to 40% of the total [CII] emission, as seen from our comparison of [CII] and HI emission. The second component is associated with optically thick clouds near regions of star formation, as seen from the three regions for which we

have computed G_0 and n.

In conclusion, we find that in NGC6946, much of the [CII] emission comes from dense PDRs on the surfaces of molecular clouds, the same clouds that are responsible for CO emission, while the HI emission appears to come from a more extended diffuse component. In NGC1313, some of the [CII] may come from low density atomic regions which also contribute to the observed HI emission; there is less CO emission associated with [CII] either because low metallicity leads to small CO cores surrounded by large [CII] envelopes or because there are very few high extinction clouds relative to diffuse clouds.

5.4. Taking the models further: diffuse vs. dense HI gas

In our modelling to this point, we have attempted to fit the observed HI emission with a single gas component: either HI gas associated with PDRs on molecular cloud edges or from diffuse interstellar clouds. In addition, we have tried to explain the [CII], [OI] and FIR emission as arising from one component. In this section, we estimate the contribution to HI column and the [CII] intensity from each of the two neutral gas components.

The origin of most of the atomic hydrogen in nearby galaxies is a controversial point. The standard picture assumes that most of the HI in galaxies is

a precursor to star formation, and arises from a diffuse HI component. However, recent high spatial resolution observations of molecular, neutral and ionized gas in nearby galaxies point toward an evolutionary picture in which a sizeable fraction of the neutral hydrogen is a product of recent star formation, resulting from photodissociation of H_2 in molecular clouds by the radiation emitted by young stars (Allen, Atherton & Tilanus (1986), Allen et al. (1997), Smith et al. (2000)). This was also suggested by the relative brightness of [CII] compared with HI line emission from galaxies in the Stacey et al. (1991) sample, which indicated that the [CII] and HI emission arose from relatively dense gas.

We want to estimate how much of the HI in NGC6946 and NGC1313 is produced by recent photodissociation of H_2 at the PDR interfaces between HII regions and molecular clouds (the "dense" component), and how much originates in diffuse gas heated by the general radiation field. The observed HI is:

$$N(HI)_{obs} = N(HI)_{dense} + N(HI)_{diff}, \tag{5}$$

where the column densities are the averages of each component within the beam. The HI diffuse component should in principle be separated into emission arising from Cold and Warm Neutral Medium (CNM, n$\sim$ 30 cm^{-3}, T$\sim$100 K, WNM, n$\sim$0.3 cm^{-3}, T$\sim$8000 K). The WNM does not contribute significantly to the [CII] emission (Wolfire et al. (1995)) whereas it might

significantly contribute the total HI diffuse emission. In what follows we neglect the WNM contribution to the diffuse HI component, because we do not have sufficient constraints for developing a three component model. Although a weakness of our model, this approximation is partially justified by observations inside and at the solar circle of the Milky Way galaxy that the CNM HI(21 cm) emission is comparable to or dominates the WNM HI(21 cm) emission (Dickey and Lockman, (1990), Kulkarni and Heiles (1987)). The WNM may dominate outer regions of HI(21 cm) emission of normal galaxies, but we point out that the regions we modelled are well inside R_{25} (see Fig. 1). Moreover, we stress that our model represents an improvement, though imperfect, over a one component model.

An equation similar to Eq. 5 holds for the observed [CII] flux coming from the neutral gas, *i.e.* with the ionized gas contribution removed:

$$I_{[CII]}^{PDR} = I_{[CII]}^{PDR_{dense}} + I_{[CII]}^{PDR_{diff}}. \tag{6}$$

In the optically thin regime, the column density of hydrogen nuclei associated with a given [CII] intensity is (Crawford et al. (1985))

$$N_{[CII]}(HI) = \frac{4.25 \times 10^{20}}{x(C)} \left[\frac{1 + 2e^{(-92/T)} + (n_{crit}/n)}{2e^{(-92/T)}} \right] I_{[CII]}^{PDR}, \tag{7}$$

where $N_{[CII]}(HI)$ is in cm^{-2}, $I_{[CII]}^{PDR}$ in erg s^{-1} cm^{-2} sr^{-1}, and $x(C)$ is the C/H gas–phase abundance ratio.

The column density of HI produced in dense gas (assuming $n = n_{dense} \gg n_{crit}$ for [CII]) is:

$$N(HI)_{dense} = \frac{4.25 \times 10^{20}}{x(C)} \left[\frac{1 + 2e^{-92/T_{dense}}}{2e^{-92/T_{dense}}}\right] I^{PDR_{dense}}_{[CII]}. \quad (8)$$

and the column density of HI associated with diffuse neutral gas is:

$$N(HI)_{diff} = \frac{4.25 \times 10^{20}}{x(C)} \left[\frac{1 + 2e^{-92/T_{diff}} + (n_{crit}/n_{diff})}{2e^{-92/T_{diff}}}\right] I^{PDR_{diff}}_{[CII]}. \quad (9)$$

Here, T_{dense} and T_{diff} are the temperatures of the dense and diffuse components, respectively.

In the limit where the density of the diffuse gas n_{diff} is much less than the critical density for the [CII] transition ($n_{crit} \simeq 3 \times 10^3\,\mathrm{cm}^{-3}$), we can solve for the [CII] intensity arising from the dense gas only:

$$I^{PDR_{dense}}_{[CII]} = I^{PDR}_{[CII]} - \frac{2x(C)N(HI)_{obs}}{4.25 \times 10^{20} e^{92/T_{diff}}} \frac{n}{n_{crit}} \quad (10)$$

where the second term on the right hand side is the [CII] intensity from the diffuse gas (see Appendix B for detailed calculation). For $T_{diff} \sim 92\ K$ and taking a diffuse component density of $30\,\mathrm{cm}^{-3}$,

$$I^{PDR_{dense}}_{[CII]} = I^{PDR}_{[CII]} - 1.73 \times 10^{-6} x(C)_{-4} N(HI)_{21}, \quad (11)$$

where $N(HI)_{21} = N(HI)_{obs}/10^{21}\,\mathrm{cm}^{-2}$. Thus, if we know n, the density in the diffuse gas, we can separate the [CII] emission from the dense and diffuse components. Finally, the column of HI arising from dense gas is:

$$N(HI)_{dense} = \frac{6.4 \times 10^{24}}{x(C)_{-4}} \left[I^{PDR}_{[CII]} - 1.73 \times 10^{-6} x(C)_{-4} N(HI)_{21} \right]. \qquad (12)$$

Tables 10 and 11 show the results of this calculation for NGC6946 and NGC1313 respectively in cases where the observed [CII] emission has been corrected for the contribution from ionized gas. In NGC6946 most of the [CII] emission observed in neutral gas, arises in dense PDRs (Col. 2 of table 9). This component seems to contribute less (a factor of 2) in the three modelled region of NGC1313 (Col. 2 of table 10), confirming that the diffuse neutral gas contribute more in the disk of NGC1313 than in NGC6946 to the total emission. Moreover, this result supports the conclusion in § 4.2, and the picture used to interpret the behaviour between [CII] intensity and HI column density presented in § 5.3.2.

The fraction of HI column density, $N(HI)_{dense}/N(HI)_{obs}$, coming from dense neutral gas in each region is listed in Col. 3 of Tables 10 and 11. We find typically that only a few percent of the HI column is associated with dense neutral gas near star forming regions. This result is in good agreement with the values published by Stacey et al. (1991) for normal galaxies. In conclusion, not much of the HI can be coming from the densest

gas in spiral arms, where recent star formation has occurred. However, our spatial resolution is insufficient to determine whether the diffuse HI, which dominated the 21 cm production, arises from recently dispersed GMCs or from an older, more pervasive interarm component. Whether much of galaxy's HI column is produced by recent photodissociation of H_2 in spiral arms remains an open question.

6. Summary and Conclusions

In this paper we presented new ISO-LWS observations in the main FIR fine structure lines of the two nearby spiral galaxies: NGC1313 and NGC6946. Both galaxies were fully mapped in the [CII (158 μm)] line with a linear resolution of $\sim$ 1.5 kpc. Some regions in NGC1313 and in NGC6946 were also observed in the [OI(63 μm)]) and the [NII(122 μm)] lines with comparable resolution.

In PDRs most of the carbon is ionized and most of the oxygen is neutral. In these regions, the atomic gas is mainly heated by photo–electrons ejected by grains after absorption of a FUV (6 eV $<$ hν $<$ 13.6 eV) photon and cools primarily *via* the [CII] and [OI] lines. Therefore, a comparison of the dust emission at MIR and FIR wavelengths to the emission in these cooling lines gives important clues on the heating/cooling processes of the atomic

medium.

Following this line of thought, Malhotra et al. (2001) and Helou et al. (2001) studied how the integrated [CII] emission of a sample of star–forming galaxies (ISO–KP) relate to the IR dust emission as a function of the overall galaxy activity as traced by the 60/100 μm IRAS colors. They found that the [CII]/FIR and [CII]/MIR ratio behave very differently. The [CII]/FIR ratio decreases with the IRAS colors whereas the [CII]/MIR stays constant. This difference has profound consequences in the understanding of the role that different dust grain populations play in the atomic gas heating/cooling process. In particular, these results confirm and strengthen the theoretical prediction that, at least in normal star–forming galaxies, PAHs are the most efficient grain population for photo–electron production (Bakes & Tielens (1994)).

The analysis in NGC1313 and NGC6946 presented in this paper had three goals:

1) investigating whether the above behaviour, found for the integrated emission of normal galaxies, holds as well in regions associated with different galaxy components like nucleus, spiral arms and diffuse disk.

2) deriving the average physical conditions (gas density n, FUV radiation field G_0 and surface temperature T_s) of the emitting clouds in the NGC1313 and NGC6946 regions observed with ISO-LWS, by applying the PDR model

predictions by Kaufman et al. (1999). The resulting parameters were also compared with the corresponding parameters found for the integrated emission of the ISO–KP galaxies.

3) comparing the observed [CII] emission in NGC1313 and NGC6946 to other gas component tracers like HI (21 cm) and ^{12}CO(1–0) in order to investigate from which component of the neutral gas (ionized medium, low and high density PDRs) the observed [CII] emission inside NGC1313 and NGC6946 arises, and if there are differences between regions associated with different galaxy components.

We summarise the main results as follows:

We found no statistical difference between the [CII]/FIR and [CII]/MIR ratios as a function of the 60/100 colors inside NGC1313 and NGC6946 and the integrated ratios of ISO–KP sample. However, the [CII]/MIR average ratios inside NGC1313 and the integrated ratios of some others irregulars (Hunter et al. (2001)) are systematically higher than the corresponding ratios in NGC6946. We show that at least inside NGC1313, this result is due to a deficiency of the carriers responsible for the Aromatic Features seen in emission at MIR wavelengths with respect to the aromatic carriers in NGC6946. This deficiency can arise either from an originally lower carbon-based grain production due to a metallicity lower than the solar value, and/or to an enhanced destruction of carriers responsible for AFE

from the intense and hard interstellar radiation field.

We did not find high (> 0.6) IRAS 60/100 μm colors even in those regions associated with HII regions or the nuclei, probably due to the relatively large beam size ($\sim$1.5 kpc) diluting the emission from the most active regions with contributions from cooler dust.

The total [CII] emission is $\sim$ 0.8% and >0.5% of the FIR emission in NGC6946 and NGC1313, respectively. Our estimation of the [CII] emission from different galaxy components leads to the result that the diffuse component associated with the disk of the galaxies is less than that found in other work (Madden et al. (1993)). In particular, we find that this component accounts for $<$ 40 % in NGC6946 and $\sim$ 30 % in NGC1313.

We applied the PDR model predictions (Kaufman et al. (1999)) to those regions of NGC6946 and NGC1313 observed in [OI], [CII] and [NII] (12 and 3 respectively), after removal of the [CII] emission arising in ionized gas. In this way we were able to derive the average parameters (n, G_0 and T_s) of the neutral atomic gas in the LWS beam. Although these values roughly agree with the parameters found for the integrated emission of the ISO–KP sample (Malhotra et al. (2001)), we find a scatter in the G_0/n ratio distribution much greater than for the ISO–KP galaxies. This variation is probably related to differences in the stellar populations and/or to differences in the mixture of active and not active components inside the LWS beam, along

the galaxies.

We do not find regions as extreme ($n > 10^4$ cm^{-3} and $G_0 > 10^4$) as some ISO–KP galaxies. Though surprising, this agrees with the fact that we did not find regions with high 60/100 ratios. We attribute this result to the fact that the typical region within the beam (1.5 kpc) is still too big, leading to a mixture of emission from active and less active regions.

In NGC6946, [CII] and ^{12}CO(1–0) are well correlated, though the average $I_{[CII]}/I_{CO}$ ratio is lower (a factor of ~ 2) than that previously found by Stacey et al. (1991) for normal galaxies. The same trend is followed by the integrated ratios of the ISO–KP sample for which CO data are available. Since higher ratios correspond to higher star formation activity, this shows that the observed [CII] emission in NGC6946 arises in regions less active than in the galaxies observed by Stacey et al. (1991), whose observations are biased towards the galaxy nuclei.

In NGC1313 we have ^{12}CO(1–0) data for only three regions. One of these follows the trend outlined by the NGC6946 and ISO–KP observations, though at the very low surface brightness end of the relation. The other two regions have a $I_{[CII]}/I_{CO}$ in agreement with that expected for more active regions even though they do not have particularly high 60/100 μm. We interpret this result as due either to a change in metallicity along the galaxy (unlikely) or to a diffuse/dense gas ratio in the LWS beam higher

than in NGC6946. Moreover, regions with similar [CII] emission have very different CO content, suggesting that the physical condition of the ISM inside NGC1313 are much less homogeneous than in NGC6946.

In NGC6946 the [CII] intensity spans more than one order of magnitude, and is independent of the HI column density. We have shown that this behaviour is mostly due to the fact that [CII] and HI arise from different gas components: the former is associated with PDRs in the interface between star forming regions and parental molecular clouds, while the latter arises principally from diffuse, low density gas.
In NGC1313 the situation is very similar to that found in NGC6946 for HI column densities $\gtrsim 10^{21}$ cm^{-2}. In this case, however, clouds optically thick in HI can explain at least part of the independence between [CII] intensity and HI column density. For HI column densities lower than 10^{21} cm^{-2} there is a weak proportionality, which corresponds to what we expected from diffuse low density (n$\sim$30 cm^{-3}) PDRs illuminated by the general FUV interstellar radiation field. Therefore, we successfully detected [CII] emission arising from two distinct gas components in NGC1313: one is associated with classical PDRs related to star forming and the other associated with the diffuse low density gas associated with HI.

In agreement with the above results, we find that very little (a few %) of the observed HI flux originates in dense ($n > n_{crit} \simeq 3\times10^{3}$ cm^{-3}) gas in the

modeled regions of NGC6946. The same result holds for two of the three regions modeled in NGC1313 (which correspond to location on the galaxy associated to bright star-froming complexes and not to the diffuse disk). In the third region, the observed [CII] emission might entirely arise in diffuse ionized gas. For all the other modeled regions (in both galaxies) the latter contribution can be significant, but not more than ∼50%.

On the other hand, most of the [CII] emission observed in NGC6946 arise in dense gas associated to star forming regions whereas this component is a factor ∼2 less in the three modelled region of NGC1313. This confirms that the diffuse atomic gas disk component contributes more in NGC1313 than in NGC6946 to the total [CII] observed emission.

A. The foreground emission estimation at 158 μm in the NGC1313 direction

To evaluate the [CII] foreground contribution for NGC1313, we calculated the [CII] flux expected for an IRAS 100 μm flux equal to the average emission around NGC1313 in the following way. To calculate the expected [CII] emission for a given infrared (IR) flux we have to know which ISM phase produces the observed IR emission: cirrus or molecular clouds. Using the FIRAS and Leiden/Dwingeloo HI data, Boulanger et al. (1996) presented the galactic IR-HI correlation in the northern hemisphere of the Milky–Way. The slope of this correlation for $W_{HI} < 250$ K km s^{-1} (N(HI)$<4.5\times10^{20}$ cm^{-2}) is 0.53. At higher column densities the correlation becomes steeper because of the increasing contribution of the molecular component. We use the Colomb, Poppel & Heiles (1980) HI observations of the southern sky to check if the IR emission around NGC1313 follows the cirrus relation. Fourteen HI measurements at $30'$ resolution were found in the $2.5^0\times2.5^0$ region centered on NGC1313. We calculate the IRAS emission at 100 μm using a $30'$ FWHM beam size in the same HI positions. According to the DIRBE Explanatory Supplement:

$$FIRAS(100\ \mu m) = 0.72 \times IRAS(100\ \mu m). \tag{A1}$$

We thus fitted a line to the HI–DIRBE relation after multiplying the IRAS flux by 0.72. The fitted slope is 0.4, as compared with 0.53 obtained from Boulanger et al. (1996). Moreover, all the HI pointings have HI column density less than 4.5 $\times 10^{20}$ cm^{-2}. We thus are confident that the bulk of the infrared emission around NGC1313 is from cirrus.

There is not a measured IRAS 100 μm – [CII] surface brightness relation for cirrus in our Galaxy. To calculate it we combined the DIRBE 100 μm – N(HI) relation published by Boulanger et al. (1996):

$$I_{100\ \mu m}^{DIRBE}(MJy/sr) = 0.53 \times N(HI)(10^{20}cm^{-2}), \tag{A2}$$

and the [CII] surface brightness – N(HI) relation evaluated by Bennett et al. (1994) for cirrus:

$$I_{C^+}(10^{-6}ergs^{-1}cm^{-2}sr^{-1}) = (2.56 \times N(HI)(10^{20}cm^{-2}))/4\pi. \tag{A3}$$

Combining these equations and taking into account also eq. A1 we obtain the following IRAS (100 μm) –[CII] relation for cirrus:

$$I_{C^+}(ergs^{-1}cm^{-2}sr^{-1})) = 0.268 \times 10^{-6} I_{100\ \mu m}(MJy/sr). \tag{A4}$$

The average IRAS 100 μm flux around NGC1313 has been obtained on the HiRes IRAS image by calculating the flux in the LWS beam in regions located randomly around the galaxy. The average emission at 100 μm thus obtained is equal to is 2.76 MJy/sr, which implies a [CII] surface brightness

equal to 0.79×10^{-6} erg s^{-1} cm^{-2} sr^{-1}). This corresponds to 11.2×10^{-14} erg s^{-1} cm^{-2}. By contrast, the [CII] emission measured with LWS in the reference point is 7×10^{-14} erg s^{-1} cm^{-2}.

B. Detailed calculation for separating the dense and diffuse components in PDRs

In this section we perform the detailed calculation which leads to Eq. (10) of Sec. 5.4. From Eq. 9 we isolate $I^{PDR_{diff}}_{[CII]}$:

$$I^{PDR_{diff}}_{[CII]} = \frac{N(HI)_{diff}\ x(C)}{4.25\times10^{20}}\ \left[\frac{2e^{(-92/T_{diff})}}{1+2e^{(-92/T_{diff})}+(n_{crit}/n_{diff})}\right] \tag{B1}$$

From Eq. 6:

$$I^{PDR_{dense}}_{[CII]} = I^{PDR_{obs}}_{[CII]} - I^{PDR_{diff}}_{[CII]} \tag{B2}$$

Substituting Eq. B1 in Eq. B2:

$$I^{PDR_{dense}}_{[CII]} = I^{PDR_{obs}}_{[CII]} - \frac{N(HI)_{diff}\ x(C)}{4.25\times10^{20}}\ \left[\frac{2e^{(-92/T_{diff})}}{1+2e^{(-92/T_{diff})}+(n_{crit}/n_{diff})}\right] \tag{B3}$$

From Eq. 5:

$$N(HI)_{diff} = N(HI)_{obs} - N(HI)_{dense} \tag{B4}$$

Substituting in Eq. B3:

$$I_{[CII]}^{PDR_{dense}} = I_{[CII]}^{PDR_{obs}} - \frac{x(C)}{4.25\times10^{20}} \left[\frac{2e^{(-92/T_{diff})}}{1+2e^{(-92/T_{diff})}+(n_{crit}/n_{diff})}\right] [N(HI)_{obs} - N(HI)_{dense}] \tag{B5}$$

Developing and taking to the left hand all terms referring to the dense component one obtains:

$$I_{[CII]}^{PDR_{dense}} - \frac{x(C)}{4.25 \times 10^{20}} \left[\frac{2e^{(-92/T_{diff})}}{1 + 2e^{(-92/T_{diff})} + (n_{crit}/n_{diff})}\right] N(HI)_{dense} = I_{[CII]}^{PDR_{obs}} - \frac{x(C)}{4.25 \times 10^{20}} \left[\frac{2e^{(-92/T_{diff})}}{1 + 2e^{(-92/T_{diff})} + (n_{crit}/n_{diff})}\right] N(HI)_{obs} \tag{B6}$$

Let's call for simplicity the right hand side of Eq. B6 A. Substituting the expression for $N(HI)_{dense}$ of Eq. 8 and factoring $I_{[CII]}^{PDR_{dense}}$:

$$I_{[CII]}^{PDR_{dense}} \left[1 - \left(\frac{1 + 2e^{(-92/T_{dense})}}{1 + 2e^{(-92/T_{diff})} + (n_{crit}/n_{diff})}\right) \left(\frac{1}{e^{(-92/T_{dense}+92/T_{diff})}}\right)\right] = A \tag{B7}$$

Since $n_{diff} \gg n_{crit}$ Eq. B7 can be approximated:

$$I_{[CII]}^{PDR_{dense}} \left[1 - \frac{n_{diff}}{n_{crit}} \left(1 + 2e^{(-92/T_{dense})}\right) \left(\frac{1}{e^{(-92/T_{dense}+92/T_{diff})}}\right)\right] \approx A \quad \text{(B8)}$$

where we have now written explicitly the term A. For T$_{diff}\sim$ 92 K and T$_{dense}\gg$ 92 K the term in the square brackets is $\approx$1. Therefore Eq. B8 becomes:

$$I_{[CII]}^{PDR_{dense}} \approx I_{[CII]}^{PDR_{obs}} - \frac{x(C)}{4.25 \times 10^{20}} \left[\frac{2e^{(-92/T_{diff})}}{1 + 2e^{(-92/T_{diff})} + (n_{crit}/n_{diff})}\right] N(HI)_{obs} \quad \text{(B9)}$$

which for $n_{diff} \ll n_{crit}$ gives:

$$I_{[CII]}^{PDR_{dense}} \approx I_{[CII]}^{PDR_{obs}} - \left[\frac{x(C)}{4.25 \times 10^{20}} \frac{n_{diff}}{n_{crit}} 2e^{(-92/T_{diff})}\right] N(HI)_{obs} \quad \text{(B10)}$$

which is Eq. 10 of Sec. 5.4.

This work was supported by ISO data analysis funding from the US National Aeronautics and Space Administration, and carried out at the Infrared Processing and Analysis Center and the Jet Propulsion Laboratory of the California Institute of Technology. ISO is an ESA project with instruments funded by ESA member states (especially the PI countries: France, Germany, the Netherlands, and the United Kingdom), and with the participation of ISAS and NASA.

The authors thank the anonymous referee for his/her very useful comments and inputs, which improved the paper.

The authors also thank M.D. Thornley, T. Helfer and M. Regan of the BIMA Survey on Normal Galaxies (SONG) team for kindly providing the unpublished ^{12}CO(1–0) data of NGC6946; F. Boulanger and F. Viallefond for the HI 21 cm data of NGC6946 and S.D. Ryder for the HI 21 cm data of NGC1313.

A. C. wish also to thank J. Lequeux and M. Gerin for very useful discussions.

M.R wishes to acknowledge support fro FONDECYT(Chile) grant No 1990881 and FONDECYT (Chile) International grant No 7990042

REFERENCES

Allamandola, L.J., Tielens, A.G.G.M., & Barker, J.R., 1989, ApJS, 71, 733

Allen, R.J., Atherton, P.D., & Tilanus, R.P.J., 1986, Nature, 319, 296

Allen, R.J., Knapen, J.H., Bohlin, R. et al. , 1997, ApJ, 487, 171

Bajaja, E., Wielebinski, R., Reuter, H.–P., et al. , 1995, A&ASS, 114, 147

Bakes, E.L.O., & Tielens, A.G.G.M., 1994, ApJ, 427, 822

Belley, J & Roy J.R., 1992, ApJSS, 78, 61

Bennett, C.L., Fixsen, D.J., Hinshaw, G.T., et al. , 1994, ApJ, 434, 587

Boulanger, F., Beichman C., Désert X.,et al. , 1988, ApJ, 332, 328

Boulanger, F., & Viallefond, F., 1992, A&A, 266, 37

Boulanger, F., Reach W. T., Abergel A., et al. , 1996, A&A, 315, L325

Boulanger, F., Abergel, A., Bernard, J.–P., et al. , 1996, A&A, 256, 262

Casoli, F., Clausset, F., Combes, F., et al. , 1990, A&A, 233, 375

Cesarsky, D., Lequeux J., Abergel A., et al. , 1996, A&A, 315, L309

Colomb, F.R., Poppel, W.G.L. & Heiles, C., 1980, A&AS, 40, 47

Contursi, A., Lequeux J., Cesarsky D., et al. , 2000, A&A, 362, 310

Crawford M. K., Genzel R., Townes C.H., et al. , 1985, ApJ, 291, 755

Dale, D.A., Helou, G., Silbermann, N., et al. , 1999, AJ, 118, 2055

Dale, D.A., Silbermann, N. Helou, G., et al. , 2000,AJ, 120, 583

Dale, D.A., Helou, G., Contursi, A., et al. , 2001, ApJ, 549, 215

de Vaucouleurs, G., de Vaucouleurs, A., Corwin, H. G., et al. , 1991, Third Reference Catalogue of Bright Galaxies (New York: Springer)

Dickey, J.M. & Lockman, F.J. 1990, ARA&A, 28, 215

Elmegreen, D. P., Chromey, F. R. & Santos, 19998, AJ, 116, 1221

Garnett D. R. & Shields G. A., 1987, ApJ, 317, 82

Garnett D. R., Shields G. A., Peimbert M., et al. , 1999, ApJ, 513,168

Gry C., Swinyard B., Harwood A., et al. , 2000, "The ISO Handbook", Vol. IV, "LWS - The long–Wavelength Spectrometer", p.78-83

Heiles C., 1994,ApJ, 436, 720

Helou, G., 1986, ApJ, 311, L33

Helou, G., Khan I., Malek L., et al. , 1988, ApJS, 68, 151

Helou, G., Ryter C. and Soifer B.T., 1991, ApJ, 376, 505

Helou, G., 1998, Highlights of Astronomy Vol. 11A, Ed. Johannes Andersen. Kluwer Academic Publishers, p.1134

Helou, G., Lu, N.Y., Werner, M.W., et al. , 2000, ApJl, 532, L21

Helou, G., Malhotra, S., Hollenbach, D., et al. , 2001, ApJl, 548, L37

Hollenbach, D. J., & Tielens, A.G.G.M., 1999, Rev. Modern Phys., 71, 173

Hunter, D. A., Kaufman, M.J., Hollenbach, D.J., et al. , 2001, ApJ, astro–ph/0012354

Isreal, F. P., H2 in Space, 1999. Eds.: F. Combes, G. Pineau des Forts. Cambridge University Press, Astrophysics Series ApJ, astro–ph/0001250

Kaufman, M.J., Wolfire, M.G., Hollenbach, D.J., et al. , 1999, ApJ, 527, 795

Kuchinski L. E.,Freedman W. L., Madore B. F. et al. , 2000, ApJ, 131, 441

Kulkarni, S.R. & Heiles, C. 1987, in *Interstellar Processes*, ed. D. Hollenbach & H. Thronson, (Dordrecht: Reidel), p87

Lequeux, J., Burlot, J., Des Frotes, G., et al. , 1994, A&A, 292, 371

Lu, N., Helou, G., et al. , 2000, in preparation

Madden, S.C., Geis, N., Genzel, R., et al. , 1993, ApJ, 407, 579

Madden, S.C., 2000, Proceedings for "*The Interplay between Stars and ISM*, New Astronomy Reviews, Eds. D. Schaerer & R. Delgado–Gonzalez

Malhotra, S., Hollenbach, D., Helou G.,et al. , 2000, ApJ, 543, 634

Malhotra, S., Kaufman, M.J., Hollenbach, D., et al. , 2001, to appear in ApJ, astro–ph/0106485

Meyer D. M., Cardelli J. A., & Sofia U. J., 1997, ApJ, 490, L103

Mollá, M. & Roy, J.–R., 1999, ApJ, 514, 781

Osterbrock D. E. *Astrophysics of Gaseous Nebulae*, San Francisco: Freeman

Pak, S., Jaffe, D. T., van Dishoeck, E. F. et al. ,1998, ApJ, 498, 835

Puget, J.–L., & Léger, A., 1989, ARA&A, 27, 161

Ryder, S.D., Staveley–Smith, L., Malin, D., et al. , 1995, AJ, 109, 1592

Rubin R. H., Simpson J. P., Erickson E. F., et al. , 1988, ApJ, 327, 377

Rubin R. H., Simpson J. P., & Walter D. K., 1993, ApJ, 413,242

Rubio, M., Lequeux J., & Boulanger F., 1993, A&A, 271, 9

Sauty, S., Gerin, M., % Casoli, F., 1998, A&A, 339,19

Scott. M., Schlegel, E.M., Robert, P., et al. , 1998, AJ, 116, 1657

Smith, D. A., Allen, R.J., Bohlin, R.C., et al. , 2000, ApJ, 538, 608

Sofia U. J., Cardelli J. A., Guerin K. P. & Mayer D. M., 1997, Apj, 482, L105

Spoon H.W.W., Keane J.V., Tielens A.G.G.M., et al. , 2001, astro–ph/0012011

Stacey, G.J., Geis, N., Genzel, R., et al. , 1991, ApJ, 373, 423

Sternberg, A., & Dalgarno, A., 1989, ApJ, 338, 197

Tielens, A.G.G.M & Hollenbach, D., 1985, ApJ, 291, 722

Walsh J.R., & Roy J.–R., 1997, MNRAS, 288, 715

Watson, W., D., 1972, ApJ, 176, 103

Weingartner, J. C., & Draine, B. T., 1999, astro–ph/9907251

Wells, B., Helou, G., Freeman, K. & Ryder, S. 1995, in *The Interplay between Massive Star Formation, the ISM, and Galaxy Evolution*, ed. D. Kunth et al. (Gif-sur-Yvette: Editions Frontieres)

Wolfire M. G., Hollenbach D., McKee C. F., et al. , 1995, ApJ, 443,152

This manuscript was prepared with the AAS LaTeX macros v5.0.

Table 1. NGC6946 and NGC1313 properties. Col. 1 : NGC names; Col. 2 and 3 : R.A. and Dec. J2000; Col. 5, 6 and 7: Semi major and minor axes at the optical (R_{25}) extent in arcmin and heliocentric velocity (km/s) (RC3, de Vaucouleurs et al. (1991)) ; Col. 8 : Distances computed in the Local Group reference frame and H_0=75 Km/s/Mpc; Col. 9 : Logarithm of the total FIR (from IRAS) over blue ratio (Table 1 of Dale et al. (2000)); Col. 10 : $f_\nu(60\ \mu m)/f_\nu(100\ \mu m)$ (IRAS color ratio IRAS values computed on HiRes IRAS images, Table 4 of Dale et al. (2000)); Col. 11 : $f_\nu(60\ \mu m)$ (Jy) flux density.

Name	R.A.	Dec.	Morph.	a	b	V_{hel}	Dist.	log(FIR/B)	F_{60}/F_{100}	F_{60}
	J2000			$'$		km/s	Mpc			Jy
NGC1313	03:18:22.24	-66:28:41.8	Sd	9.1	6.9	475	3.6	-0.43	0.47	45.7
NGC6946	20:34:51.22	60:09:17.5	Scd	11.5	9.8	48	4.5	-0.34	0.46	167.7

Table 2. LWS observations for NGC1313. Number of regions correspond to the numbers in Fig. 1. Region 50 corresponds to the galaxy center (Table 1). Errors (shown in parenthesis) derive from the line and baseline fitting and do not include the 30% calibration uncertainties. To obtained the intrinsic emission in the [CII] line first substract the foreground value (11×10^{-14} erg s^{-1} cm^{-2}) then multiply by the extended source correction factor ($\sim$0.6). The LWS beam size is: π $(75''/2)^2/\ln2=1.5\times10^{-7}$ sterad.

No.	R.A. J2000 h:m:s.s	Dec. J2000 °:′:″	[CII] flux 158 μm 10^{-14} erg s^{-1} cm^{-2}	No.	R.A. J2000 h:m:s.s	Dec. J2000 °:′:″	[CII] flux 158 μm 10^{-14} erg s^{-1} cm^{-2}
1	3:16:59.0	-66:29:57.8	<38	45	3:18:16.3	-66:32:11.0	50 (5)
2	3:17:09.3	-66:29:15.0	<43	46	3:18:17.9	-66:25:55.9	31 (7)
3	3:17:06.3	-66:30:59.0	30 (5)	47	3:18:19.2	-66:30:27.0	124 (15)
4	3:17:13.4	-66:32:00.2	38 (6)	48	3:18:20.6	-66:34:56.6	<30
5	3:17:16.6	-66:30:15.8	44 (8)	49	3:18:20.7	-66:24:11.9	29 (5)
6	3:17:19.5	-66:28:31.8	45 (5)	50	3:18:22.2	-66:28:41.9	222 (11)
7	3:17:20.8	-66:33:01.8	43 (5)	51	3:18:23.5	-66:33:12.6	56 (6)
8	3:17:23.7	-66:31:17.7	40 (5)	52	3:18:25.1	-66:26:57.8	48 (5)
9	3:17:26.8	-66:29:32.6	53 (9)	53	3:18:26.6	-66:31:27.5	58 (6)
10	3:17:27.9	-66:34:03.0	27 (4)	54	3:18:28.1	-66:25:12.7	37 (6)
11	3:17:29.8	-66:27:48.6	34 (4)	55	3:18:29.4	-66:29:43.4	101 (5)
12	3:17:31.1	-66:32:18.6	30 (7)	56	3:18:30.9	-66:34:13.1	51 (6)
13	3:17:34.0	-66:30:34.5	37 (11)	57	3:18:31.0	-66:23:28.7	32 (8)
14	3:17:35.3	-66:35:04.2	24 (5)	58	3:18:32.4	-66:27:58.3	108 (9)
15	3:17:37.1	-66:28:49.4	43 (6)	59	3:18:33.7	-66:32:29.0	31 (6)
16	3:17:38.2	-66:33:20.1	27 (8)	60	3:18:35.2	-66:26:14.3	28 (4)
17	3:17:39.9	-66:27:05.4	50 (11)	61	3:18:36.8	-66:30:43.9	68 (10)
18	3:17:41.3	-66:31:35.0	67 (9)	62	3:18:38.3	-66:24:29.1	45 (6)

Table 2—Continued

No.	R.A.	Dec.	[CII] flux	No.	R.A.	Dec.	[CII] flux
	J2000		158 μm		J2000		158 μm
	h:m:s.s	°:′:″	10^{-14} erg s^{-1} cm^{-2}		h:m:s.s	°:′:″	10^{-14} erg s^{-1} cm^{-2}
20	3:17:44.2	-66:29:51.3	63 (8)	64	3:18:41.1	-66:22:45.1	<38
21	3:17:45.6	-66:34:21.0	26 (5)	65	3:18:41.1	-66:33:29.5	36 (6)
22	3:17:47.3	-66:28:06.2	36 (7)	66	3:18:42.6	-66:27:14.7	43 (6)
23	3:17:48.4	-66:32:37.0	56 (9)	67	3:18:44.0	-66:31:45.4	42 (4.)
24	3:17:49.8	-66:37:06.9	27 (6)	68	3:18:45.4	-66:25:30.7	26 (5)
25	3:17:50.2	-66:26:22.1	48 (8)	69	3:18:47.0	-66:30:00.3	61 (5)
26	3:17:51.6	-66:30:51.8	62 (7)	70	3:18:48.4	-66:23:45.2	34 (9)
27	3:17:52.7	-66:35:22.9	38 (4)	71	3:18:49.8	-66:28:16.3	47 (5)
28	3:17:54.4	-66:29:07.8	80 (8)	72	3:18:51.3	-66:32:45.9	53 (7)
29	3:17:55.8	-66:33:37.8	36 (6)	73	3:18:52.8	-66:26:31.2	38 (6)
30	3:17:57.5	-66:27:22.7	48 (7)	74	3:18:54.2	-66:31:01.9	42 (7)
31	3:17:58.7	-66:31:53.8	57 (10)	75	3:18:55.6	-66:24:47.1	26 (6)
32	3:18:00.1	-66:36:23.4	<50	76	3:18:57.2	-66:29:16.8	45 (10)
33	3:18:00.4	-66:25:39.0	34 (6)	77	3:19:00.0	-66:27:32.7	49 (5)
34	3:18:01.8	-66:30:08.6	226 (12)	78	3:19:01.6	-66:32:02.4	44 (9)
35	3:18:03.0	-66:34:39.3	36 (11)	79	3:19:02.9	-66:25:47.2	42 (4)
36	3:18:04.6	-66:28:24.6	68 (9)	80	3:19:04.3	-66:30:18.3	45 (7)
37	3:18:06.1	-66:32:54.2	79 (9)	81	3:19:07.4	-66:28:33.2	41 (3)
38	3:18:07.7	-66:26:39.5	40 (7)	82	3:19:10.1	-66:26:49.2	37 (6)

Table 2—Continued

No.	R.A.	Dec.	[CII] flux	No.	R.A.	Dec.	[CII] flux
	J2000		158 μm		J2000		158 μm
	h:m:s.s	$^{\circ}$:$'$:$''$	10^{-14} erg s^{-1} cm^{-2}		h:m:s.s	$^{\circ}$:$'$:$''$	10^{-14} erg s^{-1} cm^{-2}
39	3:18:08.9	-66:31:10.2	118 (8)	83	3:19:11.8	-66:31:18.8	30 (7)
40	3:18:10.4	-66:35:40.2	23 (3)	84	3:19:14.6	-66:29:34.8	31 (2)
41	3:18:10.6	-66:24:55.4	40 (8)	85	3:19:17.5	-66:27:49.3	40 (7)
42	3:18:12.0	-66:29:25.1	198 (15)	86	3:19:22.0	-66:30:35.3	25 (5)
43	3:18:13.2	-66:33:56.1	43 (4)	87	3:19:24.7	-66:28:51.2	40 (6)
44	3:18:14.9	-66:27:41.0	53 (7)	88	3:19:32.0	-66:29:51.3	36 (10)

Table 3. LWS line flux measurements of three regions in NGC1313 observed in more than one FIR fine structure line. Region 89 is close to the galaxy's center.

No.	R.A.	Dec.	[CII] flux	[OI] flux	[NII] flux	[OIII]
	J2000		158 μm	63 μm	122 μm	88 μ
	h:m:s.s	$^{\circ}$:$'$:$''$	10^{-14} erg s^{-1} cm^{-2}	10^{-14} erg s^{-1} cm^{-2}	10^{-14} erg s^{-1} cm^{-2}	10^{-14} erg s
89	3:18:26.9	-66:28:36.5	237 (8)	113 (16)	<22	··
90	3:18:09.0	-66:29:59.6	206 (10)	133 (18)	<15	164 (
91	3:18:04.2	-66:32:29.4	79 (9)	44 (9)	<20	··

Table 4. LWS observations for NGC6946. Numbers corresponds to the numbers in Fig. 1. Region 31 corresponds to the galaxy center. The foreground value is 31×10^{-14} erg s^{-1} cm^{-2}.

No.	R.A.	Dec.	[CII]	[OI]	[OI]	[NI
	J2000		158 μm	63 μm	145 μm	122 μ
	h:m:s.s	°:′:″	10^{-14} erg s^{-1} cm^{-2}	10^{-14} erg s^{-1} cm^{-2}	10^{-14} erg s^{-1} cm^{-2}	10^{-14} erg s
1	20:35:34.9	60:02:57.8	<35	···	···	···
2	20:34:00.3	60:03:53.3	<54	···	···	···
3	20:35:26.1	60:04:13.1	<42	···	···	···
4	20:34:48.3	60:04:35.7	52 (4)	···	···	···
5	20:34:38.7	60:04:41.5	117 (11)	···	···	···
6	20:34:10.5	60:04:57.7	<65	···	···	···
7	20:35:17.3	60:05:27.9	41 (7)	···	···	···
8	20:34:58.4	60:05:40.2	69 (9)	···	···	···
9	20:34:48.9	60:05:46.3	145 (15)	···	···	···
10	20:34:39.5	60:05:51.7	108 (5)	57 (8)	···	···
11	20:34:30.0	60:05:57.8	60 (11)	···	···	···
12	20:34:20.7	60:06:02.5	<49	···	···	···
13	20:35:08.7	60:06:45.0	139 (7)	···	···	···
14	20:34:59.1	60:06:51.1	153 (13)	···	···	···
15	20:34:49.6	60:06:56.5	304 (8)	141 (10)	···	18 (
16	20:34:40.1	60:07:01.9	172 (9)	···	···	···
17	20:34:30.8	60:07:08.0	111 (42)	39 (8)	···	···
18	20:34:21.4	60:07:14.2	81 (11)	···	···	···
29	20:35:18.8	60:07:49.8	89 (7)	···	···	···

Table 4—Continued

No.	R.A.	Dec.	[CII]	[OI]	[OI]	[NI
	J2000		158 μm	63 μm	145 μm	122 μ
	h:m:s.s	$^\circ$:$'$:$''$	10^{-14} erg s^{-1} cm^{-2}	10^{-14} erg s^{-1} cm^{-2}	10^{-14} erg s^{-1} cm^{-2}	10^{-14} erg s
20	20:35:09.3	60:07:55.9	211 (9)	···	···	···
21	20:34:59.9	60:08:02.0	394 (12)	158 (14)	···	<38
22	20:34:50.3	60:08:06.7	492 (31)	···	···	···
23	20:34:41.0	60:08:12.8	357 (9)	205 (18)	···	37 (1
24	20:34:31.6	60:08:18.9	284 (13)	···	···	···
25	20:34:22.1	60:08:24.0	122 (5)	45 (9)	···	···
26	20:34:12.7	60:08:29.8	42 (7)	···	···	···
27	20:35:29.1	60:08:54.2	64 (4)	···	···	···
28	20:35:19.6	60:09:00.4	224 (11)	···	···	···
29	20:35:10.1	60:09:06.1	500 (16)	211 (26)	···	46 (7
30	20:35:00.6	60:09:11.1	489 (14)	···	···	···
31	20:34:51.2	60:09:17.6	1045 (21)	606 (80)	39 (7)	107 (2
32	20:34:41.8	60:09:23.8	354 (16)	···	···	···
33	20:34:32.3	60:09:28.8	222 (7)	117 (11)	···	18 (3
34	20:34:22.8	60:09:34.2	164 (12)	···	···	···
35	20:35:29.7	60:10:05.1	144 (8)	···	···	···
36	20:35:20.3	60:10:11.3	311 (15)	123 (17)	···	17 (2
37	20:35:10.8	60:10:16.0	401 (15)	···	···	···
38	20:35:01.4	60:10:22.4	447 (18)	191 (15)	···	58 (1

Table 4—Continued

No.	R.A.	Dec.	[CII]	[OI]	[OI]	[NII
	J2000		158 μm	63 μm	145 μm	122 μ
	h:m:s.s	°:′:″	10^{-14} erg s^{-1} cm^{-2}	10^{-14} erg s^{-1} cm^{-2}	10^{-14} erg s^{-1} cm^{-2}	10^{-14} erg s
39	20:34:52.0	60:10:28.5	468 (14)	···	···	···
40	20:34:42.5	60:10:33.6	264 (8)	136 (9)	···	17 (4
41	20:34:33.0	60:10:39.0	297 (19)	···	···	···
42	20:35:21.0	60:11:20.4	131 (6)	···	···	···
43	20:35:11.6	60:11:27.2	304 (11)	157 (17)	···	19 (6
44	20:35:02.2	60:11:33.0	284 (10)	···	···	···
45	20:34:52.7	60:11:38.4	191 (7)	56 (10)	···	12 (2
46	20:34:43.2	60:11:43.8	152 (13)	···	···	···
47	20:34:33.7	60:11:49.9	259 (11)	110 (11)	···	11 (3
48	20:35:21.7	60:12:32.4	61 (<)	···	···	···
49	20:35:12.4	60:12:37.8	61 (9)	···	···	···
50	20:35:02.8	60:12:43.2	101 (7)	<44	···	···
51	20:34:53.5	60:12:48.6	165 (10)	···	···	···
52	20:34:25.0	60:13:05.9	68 (4)	···	···	···
53	20:35:31.9	60:13:36.8	35 (<)	···	···	···
54	20:35:03.7	60:13:53.0	25 (6)	···	···	···
55	20:34:16.4	60:14:22.2	43 (3)	···	···	···
56	20:35:42.1	60:14:41.6	47 (<)	···	···	···

Table 5. PDR model solutions for regions in NGC6946 observed in the [CII(158 μm],[OI(63 μm] and NII(122 μm] lines. Col. 1: Type of ionized medium (IM) contributing to the [CII] observed flux. Col. 2, 3 and 4: n, G_0/n and T_s model solutions for the [CII] arising in PDR only. Col. 5 Area filling factor for regions in PDR emitting the observed [CII] contained in the LWS beam. Col. 6 : Percentage of [CII] emission coming from ionized gas.

Type	n	$\frac{G_0}{n}$	T_s	Φ_A	IM
	cm^{-3}		K		%
(1)	(2)	(3)	(4)	(5)	(6)
		NGC6946			
		n. 15			
DIM	1.8e3	0.2	229	0.02	28%
HII	3.1e3	0.2	191	0.04	1.6%
		n. 21			
DIM	1.8e3	0.5	307	0.02	<35%
HII	1.0e3	0.3	234	0.04	<2.0%
		n. 23			
DIM	3.1e3	0.3	300	0.01	48%
HII	1.0e3	0.3	234	0.04	2.8%
		n. 29			
DIM	1.0e3	1.0	320	0.02	42%
HII	3.1e2	1.0	270	0.09	2.4%
		n. 31			
DIM	1.8e3	0.5	307	0.05	45%
HII	1.0e3	0.3	234	0.12	2.6%
		n. 33			
DIM	3.1e4	< 0.1	<100	>1	41%

Table 5—Continued

Type	n	$\frac{G_0}{n}$	T_s	Φ_A	IM
	cm^{-3}		K		%
(1)	(2)	(3)	(4)	(5)	(6)
		n. 38			
DIM	3.1e3	1.0	347	0.01	60%
HII	5.6e2	0.5	245	0.06	3.5%
		n. 40			
DIM	1.8e3	0.1	221	0.02	32%
HII	1.8e3	0.1	191	0.03	0.2%
		n. 43			
DIM	3.1e3	0.1	221	0.02	30%
HII	3.1e3	0.05	181	0.03	1.7%
		n. 45			
DIM	3.1e2	1.8	337	0.02	33%
HII	1.0e1	3.1	889	0.4	1.9%
		n. 47			
DIM	1.8e3	0.2	229	0.02	21%
HII	1.8e3	0.1	191	0.03	1.2%

Table 6. Same as Table 5 but for NGC1313.

Type	n	$\frac{G_0}{n}$	T$_s$	Φ_A	IM
	cm^{-3}		K		%
(1)	(2)	(3)	(4)	(5)	(6)
		NGC1313			
		n. 89			
DIM	1.8e3	0.3	268	0.01	<42%
HII	1.8e3	0.1	191	0.03	< 2%
		n. 90			
DIM	3.1e3	0.2	262	0.01	<32%
HII	1.8e3	0.2	229	0.02	< 2%
		n. 91			
DIM	···	···	···	···	100%
HII	1.8e3	0.1	191	0.008	< 7%

Table 7. ^{12}CO(1–0) intensities in the LWS beam of those regions inside NGC6946 included in the CO BIMA-SONG map.

No.	No R.A.	Dec.	I(^{12}CO(1-0))
	J2000		K km s^{-1}
(1)	(2)		(3))
17	20:34:30.8	60:07:08.04	3.583
24	20:34:31.6	60:08:18.96	4.943
33	20:34:32.3	60:09:28.80	3.835
41	20:34:33.0	60:10:39.01	3.925
47	20:34:33.8	60:11:49.92	2.97
16	20:34:40.1	60:07:01.92	4.63
23	20:34:41.0	60:08:12.85	9.427
32	20:34:41.8	60:09:23.76	10.22
40	20:34:42.5	60:10:33.60	5.508
46	20:34:43.2	60:11:43.80	2.64
15	20:34:49.6	60:06:56.52	7.622
22	20:34:50.3	60:08:06.72	19.07
31	20:34:51.2	60:09:17.64	30.36
39	20:34:52.0	60:10:28.56	12.32
45	20:34:52.7	60:11:38.40	4.032
14	20:34:59.1	60:06:51.12	5.785
21	20:34:59.9	60:08:02.04	11.72
30	20:35:00.6	60:09:11.16	16.2
38	20:35:01.4	60:10:22.44	9.443

Table 7—Continued

No.	No R.A.	Dec.	I(^{12}CO(1-0))
	J2000		K km s^{-1}
(1)	(2)		(3))
44	20:35:02.2	60:11:33.00	5.551
13	20:35:08.7	60:06:45.00	4.227
20	20:35:09.3	60:07:55.91	6.317
29	20:35:10.1	60:09:06.12	7.775
37	20:35:10.8	60:10:15.96	6.526
43	20:35:11.6	60:11:27.24	3.907

Note. — 1 K km s^{-1} = 3.39×10^{-9} erg s^{-1} cm^{-2} sr^{-1}

Table 8. ^{12}CO(1–0) intensities in the LWS beam of three regions in NGC1313. CO data are from SEST and they will presented in a future paper by Rubio et al. (in preparation).

No.	No R.A.	Dec.	I(^{12}CO(1-0))
	J2000		K km s^{-1}
(1)	(2)		(3))
89	3:18:09.0	-66:28:36.5	0.48
90	3:18:09.0	-66:29:59.6	0.58
69	3:18:47.0	-66:30:00.3	0.79

Note. — 1 K km s^{-1} = 1.6×10^{-9} erg s^{-1} cm^{-2} sr^{-1}

Table 9. LWS beam averaged atomic hydgrogen, molecular hydrogen and total hydrogen nucleus column densities for regions 69, 89 and 90 in NGC1313. $N(H_2)$ has been derived from CO intensities assuming a conversion factor $X=1.6\times10^{21}$ cm^{-2} calculated from Eq. 3.2 of Israel 1999 and taking into account the average metallicity of NGC1313.

No.	N(HI)	$N(H_2)$	$N(HI)+2\times N(H_2)$
	10^{21} cm^{-2}	10^{21} cm^{-2}	10^{21} cm^{-2}
(1)	(2)	(3))	(4)
69	0.9	1.2	3.5
89	1.4	0.7	2.9
90	1.2	0.9	3.0

Table 10. Percentage of [CII] emission and HI column density arising from dense gas as defined in §5.4, for those regions of NGC6946 observed in the [CII(158 μm)], [OI(63 μm)] and NII(122 μm)] lines and corresponding PDR model solutions. Col. (1): Type of ionized medium (IM) contributing to the [CII] observed flux. Col. (2) and (3): Percentage of [CII] emission and HI column density arising in dense (n$\gg 3\times10^3$ cm^{-3}) atomic gas. Col. (4) and (5): n and G_0 model solutions for the dense gas component only.

Type IM	CII^d	HI^d	n^d	G$_0^d$
	%	%	cm^{-3}	
(1)	(2)	(3)	(4)	(5)
	NGC6946			
	n. 15			
DIM	74%	3.7%	1.8e3	5.6e2
HII	81%	6.0%	1.8e3	3.1e2
	n. 21			
DIM	<78%	<5.0%	1.8e3	1.0e3
HII	<87%	<9.0%	1.0e3	3.1e2
	n. 23			
DIM	72%	4.0%	3.1e3	1.8e3
HII	85%	7.8%	1.8e3	5.6e2
	n. 29			
DIM	80%	5.6%	1.8e3	1.8e3
HII	89%	9.4%	5.6e2	5.6e2
	n. 31			
DIM	92%	14%	1.8e3	1.0e3
HII	95%	25%	1.0e3	3.1e2
	n. 33			

Table 10—Continued

Type IM	CII^d	HI^d	n^d	G_0^d
	%	%	cm^{-3}	
(1)	(2)	(3)	(4)	(5)
	n. 38			
DIM	73%	4.0%	3.1e3	3.1e3
HII	89%	10%	1.0e3	5.6e2
	n. 40			
DIM	70%	3.7%	3.1e3	5.6e2
HII	79%	5.4%	3.1e3	3.1e2
	n. 43			
DIM	75%	4.4%	3.1e3	3.1e2
HII	82%	6.2%	3.1e3	1.8e2
	n. 45			
DIM	61%	2.8%	1.0e3	1.8e3
HII	73%	4.2%	3.1e2	5.6e2
	n. 47			
DIM	71%	3.9%	1.8e3	5.6e2
HII	78%	4.8%	1.8e3	3.1e2

Table 11. Same as Table 10 but for NGC1313.

Type	CII^{d}	HI^{d}	n^{d}	G$_{0}^{d}$
	%	%	cm^{-3}	
(1)	(2)	(3)	(4)	(5)
		NGC1313		
		n. 89		
DIM	<36%	<1.7%	1.8e3	5.6e3
HII	<62%	<3.0%	1.8e3	3.1e2
		n. 90		
DIM	<45%	<2.0%	1.8e3	5.6e3
HII	<62%	<3.0%	5.6e2	3.1e3
		n. 91		
DIM	...	...	...	...
HII	<4.5%	<1.0%	3.1e5	1.0e1

Fig. 1.— The LWS pointings at different wavelengths on HI maps for NGC1313 (Ryder et al. 1995, resoltuion equal to $29'' \times 28''$; top panel) and NGC6946 (Boulanger & Viallefond 1992, resolution equal to $24.5'' \times 28.3''$; bottom panel). LWS pointings are represented by circles of diameter equal to the FHWM of the LWS beam at 158 μm ($75''$). Black ellipses represent the optical sizes of the galaxies at surface brightness equal to 25^{th} magnitude in the B band (R_{25}). Top panel: NGC1313. All fields indicated by circles were observed at 158 μm. Blue circles correspond to pointings observed at 63 μm and 122 μm. Bottom panel: NGC6946. All circles were observed at 158 μm. Blue, green and yellow circles correspond to the pointings observed at 63 μm; green and yellow circles at 122 μm, yellow circles at 88 μm.

Fig. 2.— HI contours superposed on an IRAS map at 100 μm of NGC1313 (grey scale). The position of the point observed by LWS to measure the [CII] foreground emission is marked (REF). Note the elevated levels of Galactic cirrus in the direction of NGC1313 and the lower foreground emission around the reference position observed with LWS.

Fig. 3.— The NGC1313 (top) and NGC6946 (bottom) [CII] contours superposed on the LW2 (6.75 μm) ISOCAM images (Dale et al. 2000). Only the [CII] flux values higher than 5 σ, after background subtraction, have been considered for the interpolation. The contour levels for NGC6946 go from 1.6 to 20×10^{-6} erg s^{-1} cm^{-2}sr^{-1} with 0.8×10^{-6} erg s^{-1} cm^{-2}sr^{-1} spacing. For NGC1313 they go from 1.8 to 9.5×10^{-6} erg s^{-1} cm^{-2}sr^{-1} with 0.4×10^{-6} erg s^{-1} cm^{-2}sr^{-1} step.

Fig. 4.— Top panel: log ([CII]/FIR) as a function of 60/100 μm ratio which is indicative of the radiation field intensity. The 5σ detections at 158 μm inside NGC1313 and NGC6946 are plotted together with the global ratios of a sample of 60 normal galaxies (Malhotra et al. 2000, 2001). The Irregular galaxies belonging to the ISO–KP sample are marked with large squares and three regions inside IC10 with asterisks (Hunter et al. 2001). Bottom panel: same as the top panel but for log([CII]/ν f_ν(5-10 μm)). The ν f_ν(5-10μm) represents the contribution of the Aromatic Feature Emission between 5 and 10 μm. This quantity has been derived from the ISOCAM LW2 (5–8.5 μm) observations as in Helou et al. (2001). For display purpose we do not plot the single error measurements but the average errors are marked in the legend symbols. The upper limits with the highest 60/100 μm ratio among the whole sample of 60 normal galaxies represents NGC4418. As explained in Helou et al. (2000) and Lu et al. (2000), the MIR spectrum of this galaxy differs from the typical spectra of normal galaxies, indicating that for this galaxy the flux between 5 and 10 μm does not arise from the classical carriers producing AFE. See also Spoon et al. (2001).

Fig. 5.— Top left panel: the histogram of the log ([CII]/FIR) ratio for NGC6946 and NGC1313. Top right panel:the histogram of the log ([CII]/ν f_ν(5-10 μm)) ratio for NGC6946 and NGC1313. Middle left panel: the logarithm of the FIR flux (per beam) distribution. Middle right panel: the logarithm of the ν f(5-10μm) flux (per beam) distribution. Bottom left panel: the logarithm of the [CII] flux (per beam) distribution. Bottom right panel: the histogram of the ν f(5-10μm)/FIR ratios. The symbol m ands σ indicate the mean value of the distribution and its σ respectively.

Fig. 6.— Top. North–East South–West cut of NGC6946 with P.A. =45° along the LWS pointings. For each wavelength, the intensities are normalized to the maximum value. Bottom: same as the top panel but with a P.A. = 135°.

Fig. 7.— Results from the PDR model by Kaufman et al. 1999 for the regions observed with LWS in NGC6946 (triangles) and NGC1313 (circles). Only those regions with [OI(63 μm)], [NII(122 μm)] and [CII(158 μm)] have been used. Also plotted, the results obtained from the integrated emission of the ISO–KP sample by Malhotra et al. 2001 (stars) and the values of G_0 and n obtained averaging the results of the regions considered in NGC6946 (filled triangle).

Fig. 8.— Regions in NGC6946 observed in the [CII(158 μm)], OI(63 μm)] and NII(122 μm)] fine structure lines with LWS, for which it has been possible to apply the model predictions of Kaufman et al. (1999). The grey scale is the ISOCAM LW2 (5–8.5 μm) image (Dale et al. 2000). The MIR surface brightness is higher in dense and warm PDRs.

Fig. 9.— [CII(158 μm)] intensities as a function of the ^{12}CO(1–0) intensities for regions in NGC6946 (triangles), NGC1313 (open circles), galaxies of the ISO–KP for which CO data are available (Lord et al. in preparation, stars) and KAO data at 158 μm for the Stacey et al. (1991) sample (squares). Filled squares represent the warmer galaxies of the Stacey sample. The dashed line represents the relation followed by warm galaxies and Galactic star forming regions with a mean $I_{[CII]}/I_{CO}$ ratio of about 4200. The solid line represents the relation followed by cooler normal spirals, with mean ratio 1300.

Fig. 10.— The deprojected [CII] surface brightness vs. the deprojected HI column density for NGC1313 (circles) and NGC6946 (triangles). Also plotted as squares is the sample from Stacey et al. (1991). Within the Stacey sample is the integrated emission of the nucleus (55″) of NGC6946, marked on the figure with an asterisk. The dashed horizontal lines correspond to the Nucleus (N), Spiral Arms (SA) and Extended (E) emission component from Madden et al. (1993). The solid lines correspond to the calculated [CII] emission from standard HI clouds (n$\sim$ 30 and T$\sim$ 100, Eq. A2 from Crawford et al. 1985 1985) and that of the intercloud medium (n$\sim$ 0.1 and T$\sim 10^4$ Eq. A3 of Crawford et al. 1985) assuming area filling factors equal to unity. The dashed diagonal line represents the observed galactic cirrus emission (Bennett et al. 1994).

Fig. 11.— The CII [(158 μm)]/[NII[122 μm)] ratio as a function of the [CII]/HI ratio for those regions observed at 122 μm in NGC6946 (triangles) and NGC1313 (circles).

This figure "contursi.fig4.jpg" is available in "jpg" format from:

http://arXiv.org/ps/astro-ph/0204241v1